BLDS Pressure Belt

Final Design Report

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Team

F61 Pressure Belt

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Statement of Disclaimer

Abstract

In the aerospace industry, measurement of surface pressure distributions on aircraft wings is a great method for testing designs and for analysis purposes such as confirming CFD models. Current methods for obtaining this data include the use of pressure belts. However, the manufacturing and installation process for these devices has proven extremely tedious and inefficient. This project aims to create a more robust design for pressure measurements that improves manufacturing and installation efficiency, while providing improved compact, aerodynamic form factor. The following report illustrates the preliminary research, the specific scope of work, and the final design. The selected design concept consists of a 3D printed mold used to cast a pressure belt from a two-part silicone. This report details the manufacturing process and testing of our final design.

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1.0 Introduction

Our client, Dr. Russell Westphal, uses his Boundary Layer Data System (*BLDS*) to perform flight tests on the boundary layers that develop across aircraft wings. The current BLDS can measure the stagnation pressure at different heights off a wing. Dr. Westphal would like to also measure the static pressure field on the surface of an aircraft. From this data he can determine the overall pressure field and validate his measurements. We have designed a 'pressure belt', a flexible silicone array of pressure ports and vias that is used to transmit pressures to the BLDS. This report represents our Final Design Review and demonstrates our belt design and manufacturing process as well as its associated testing verification.

Figure 1.1 Dr. Westphal's BLDS in its current iteration. The system attaches to the wing and measures stagnation pressures at different heights off the wing surface.

2.0 Background

2.1 - Reasons for Measuring Pressure Distributions

An important test in aircraft manufacture is the flight load survey. This involves mapping the pressures across the aircraft body to determine the loads on the airframe. This survey can be used to justify design modifications, which allows for improvements to be made to the airframe. Other reasons for measuring the flight load are to allow for the models produced in computational fluid dynamics (*CFD*) software and through wind tunnel testing to be validated. Laminar to turbulent transitions are difficult to accurately predict using CFD software. For wind tunnel testing, there are certain factors, such as surface roughness, that are hard to scale down to a wind tunnel model. In short, the most accurate way to measure the fluid characteristics around an aircraft, is to directly measure them in a real-time flight test.

Overall pressure distribution measurement on an aircraft is especially useful for acquiring data at high angles of attack, near the stall condition of the aircraft. This allows the flow separation during to be measured during stall. The pressure distribution is also important for studying transonic flight dynamics. Currently, pressure fields can be back-calculated from other flight test data, however, having a direct measurement device both lowers the amount of computation necessary to acquire a pressure distribution, and can verify the results of these back-calculations. The pressure belt is not limited to strictly wing data, considering its general flexibility, and allows for testing in places that static pressure taps would not usually be able to reach (such as inlet ducts). The only real limitation for where the pressure belt can take data is the setup protocol, making the device itself incredibly flexible. All these reasons are why a system to measure pressure distributions is needed for flight testing.

2.2 - Previous Solutions

A previously attempted solution by the NACA involved sweating together a series of copper tubes in parallel and drilling a pressure port at the desired point of measurement along the longitudinal axis of a tube [Corson]. Then manometers or some other type of pressure sensor could be attached to the ends of the device to gather an array of pressure measurements. This set up can be seen in Figure 2.1 below.

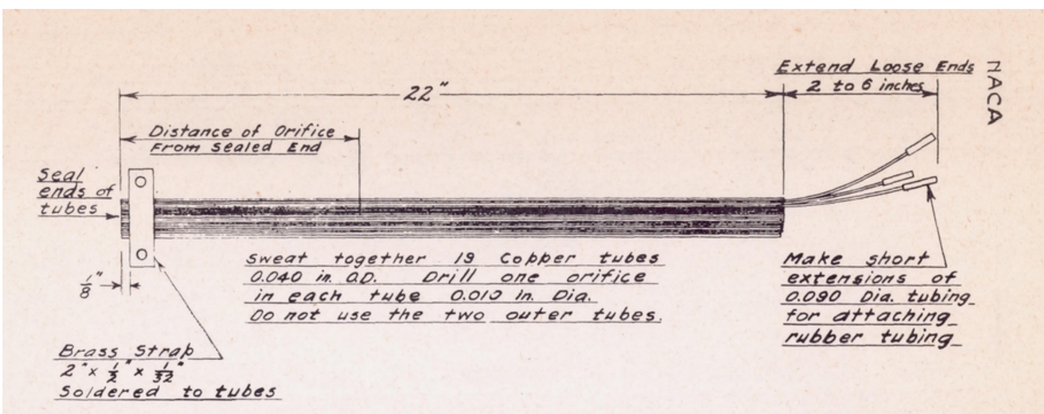


Figure 2.1 NACA design from 1943 for a superficial pressure sensor which could be temporarily attached to the wing of an aircraft.

This solution had drawbacks because the copper was rigid and could not be formed to the shape of an airfoil, nor could it be easily attached to the body of interest.

More recent commercial advancements are connected ribbons of plastic tubes, like the ones made by the company Pneumadyne. This was similar in concept to the NACA design, but due to being made from plastic tubing, the tubes are flexible and conform easily to the wing.

Figure 2.2 Plastic Ribbon Tubing

Drawbacks of using this method is the fact that the plastic tubes need to be adapted off the shelf, which involves difficult hole drilling, and a lot of setup time. Another drawback to this system is that the tubing's rigidity is fixed by the manufacturer, and currently available products are stiffer than our client would like. Also, the tubing's cross section is ridged, which both disrupts the flow, unless it is specially faired, and makes it difficult to adhere to the surface of the wing.

Another studied method of measuring pressure distribution would be through the use of distributed pressure sensors on the wing. Boeing and other university teams studied this method and its viability [Tanielian]. Considerations must be taken into account, however, to properly interface with the BLDS, and to properly attach the sensors to the wing. The currently available pressure transducers are not designed to be used in an array like we would need but are instead intended to be stand-alone devices. Significant alterations would need to be made to the transducer's hardware and firmware to adapt them to our purposes.

No known patents exist for this type of temporary static pressure measurement device; however, we suspect that some aerospace companies have their own proprietary systems which have not been made publicly available. Static pressure measurements are particularly important when concerned with fuel economy, catering to planes that need maximum loiter time (i.e., spy planes or drones). As such, data collection systems for such projects are typically built in-house, and information regarding manufacturability or function are proprietary.

2.3 - Manufacturing Avenues

Because of the flexibility requirements of our problem, we have mostly considered thermoplastic elastomers and rubbers as the primary material for our design. However, these materials cannot be easily machined or cut due to their lack of rigidity and tendency to gum-up when in contact with a machine head. This makes it difficult to create complex geometries and internal features.

The three primary methods of thermoplastic fabrication are through 3D printing, resin casting, or extrusion. The extrusion option is infeasible for us because we lack the equipment and tooling required to do it well, and generally extruding dies are used for large volume applications, as opposed to small one-off prototypes. However, the casting and 3D printing options hold a lot of promise as they offer the ability to rapid-prototype and make variable length parts relatively easily.

Another avenue to explore is the electronic pressure transducer system. This approach would daisy-chain miniature pressure transducers at various locations along the wing, with each wired back to the BLDS' internal data acquisition chip. This would be a significant break from the previously designed systems and would require the most up-front design on our part. However, the system would be minimally intrusive, highly versatile, and potentially easier to install. Two specific transducers that were recommended to us are the Bosch BMP 388, and the MPR LS [Westphal, 2020].

2.4 - Existing Patents

Shown below are a list of relevant patents to our design. They are primarily different devices used to measure either static, dynamic, or stagnation pressures in the boundary layer of a flow. They vary in their use of electric or manometer pressure sensors, and in how they are faired or attached to the surface of the airfoil.

Additionally, there is one patent for an additive which mixes into a catalyzed resin, and makes it cure flexibly. This can be useful for our project to allow us to use certain resins that we would otherwise not be able to use.

Table 2.1 Patents on devices that are similar to the pressure belt, or that could be useful to the manufacturing of the belt.

Patent Name	Patent Number	Key Characteristics
Pressure Sensor	US6272936B1	Array of electronic pressure transducers Built in control unit
Turbulent boundary layer thickness estimation method and apparatus	US20040065146A1	Measures boundary layer vertically from wing. Does not take static pressures. Uses electronic sensors
Boundary layer flow sensor	US 201414261594	Sensor embeds in wing and measures static pressure flush at the surface. Determines when boundary layer trips turbulent. Uses electronic sensors
Flexible polyester resins	US3214491A	Polyester additive that can make resin cure flexible.
Probe for measuring static pressure and turbulence intensity in fluid streams	US5233865A	Measures static pressures at locations along the flow. Uses manometer system. Faired in the front

2.5 - Wing Attachment Considerations

Our sponsor has proposed two options for attaching the belt to the wing. The ideal option is to use a light-duty adhesive called transfer adhesive, made by 3M. This is a material he has had success with previously and uses for other components of the BLDS. The transfer adhesive has a short cure time and peels off very easily without leaving any residue or other blemish on the surface of adhesion.

However, if the belt is too tall, the aerodynamic drag forces on the belt might exceed the capacity of the adhesive. In that case, we will use a viscoelastic chemical adhesive to hold the belt in place. Our sponsor also has experience with this material but would rather avoid it because it creates a more permanent bond and requires a 25psig pressure to cure properly. The viscoelastic adhesive is more difficult to remove cleanly from the aircraft and would likely be impossible to remove from our belt, making each belt a one-time use.

In addition to the adhesive, aluminum “speed-tape” will be applied to the edges of the belt both for aerodynamic purposes, and to help keep the belt seated. On an airfoil, the belt may need to wrap around the leading edge to minimize bluff body effects, which increases the necessary holding capacity of the adhesive as the belt will try to “snap back” to a straight line. These attachment considerations were major factors in determining the height specification of our belt.

3.0 Objectives

The problem statement is as follows: Dr. Westphal is a seasoned aerospace professional who specializes in on-board flight instrumentation systems. He needs a way to gather static pressure measurements that complements the systems he has already designed, while also minimizing the aerodynamic disturbances induced by the measurement system. Surprisingly, most of these devices are developed in-house, so no commercially available alternative is available.

Our boundary diagram (shown below) displays how our product will interact with Dr. Westphal’s BLDS and the aircraft in general. The scope of our project is limited to the actual pressure ports that line the wingspan, and an interfacing system that works with the BLDS. We can interface with the BLDS either electronically through a built in DAQ, or through pressure taps on the exterior of the BLDS. We are not responsible for devising the system used to adhere the belt to the wing, however, it is important for us to consider which designs are easiest or most difficult to integrate with the wing.

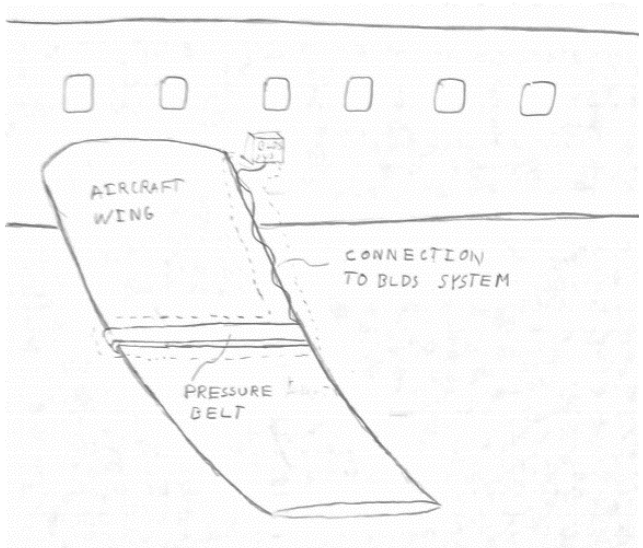


Figure 3.1 Boundary Diagram

3.1 - Wants/Needs Table:

The wants and needs table below (Table 3.1) was generated after careful discussion with our sponsor. The main purpose of our product is to measure the pressure distribution while in conjunction with Dr. Westphal's BLDS. The dimensions of the product are also critical. Furthermore, these specifications are considered needs and must be a part of the final design. Although the cost of the product, wing conformance, and ease of manufacture and installation are not considered needs, there will certainly be an attempt to incorporate these aspects into the final product. Also, a functional decomposition is provided in Figure 3.2.

Table 3.1 Wants and needs table

Need	Want
Accurately measure pressure distributions	Cheap (under $1000 budget)
Connects to BLDS	Easy to manufacture/install
Does not affect flow	Flexible/conforms to wing
Flexible port placement	Variable length
2" max width	Characterization of flow effects
0.15" max height	
0.020-0.040" port size	
Variable number of ports	

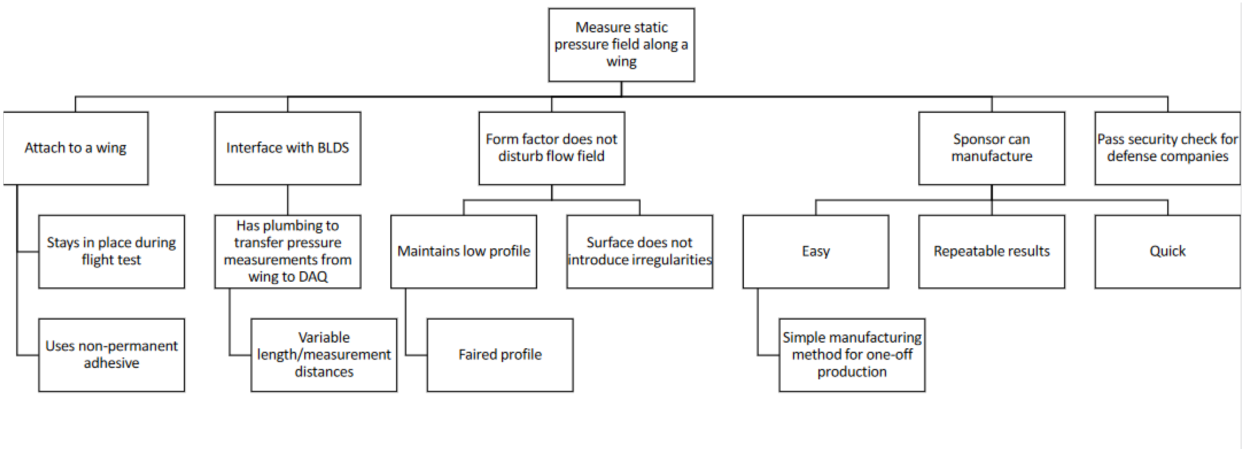


Figure 3.2 Functional decomposition of our pressure belt

3.2 - QFD Process:

The Quality Function Deployment method, otherwise known as the House of Quality, is a process used to fully define the problem. The QFD for this project is attached in Appendix A. The House of Quality is broken up into different sections including the who, what, how, how much, now and intersections between these distinct groups. In other words, this process focuses on the customers, their wants and needs, quantitative targets, how these needs will be tested in a new product, current products available, and how each of these categories interact with one another. From our QFD, we can see that each customer requirement is addressed by at least one engineering specification, meaning that the problem is fully defined.

3.3 - Engineering Specifications

Table 3.2 Table of target specifications for our design

Spec #	Specification Description	Requirement or Target (units)	Tolerance	Risk	Compliance
1	Number of Pressure ports	8	Max	M	I
2	Size of ports	0.020 - 0.040"	Min	M	I
3	Size of vias	0.040”	Min	M	I
4	Connect to standard pressure tubing	Fit within tolerance	±0.005"	L	T,I
5	Pressure Accuracy/Precision	~5% of known data	Min	H	T,A
6	Cost	$1,000	±$200	L	I
7	Width of belt	2"	Min	L	I
8	Manufacturing Repeatability	2	Max	H	I
9	Shore 00 Hardness	40	±10	L	I
10	Installation time	<5 hours	±2 hours	H	T
11	Height of belt	0.150"	Min	M	I
12	Surface roughness	63 microinches	±5	M	I

*Compliance terms refer to Test (T), Analysis (A), Inspection (I), and Similarity (S).

The number of pressure ports is something we want to maximize, as that will allow for the greatest number of data points for a pressure distribution. The size of ports must be minimized to ensure that the static pressure is accurately measured at a single point. The system must be able to connect to the tubing on the BLDS. Measurement accuracy is critical so that we know the output can be trusted. Cost is a specification to be minimized to allow for cheap manufacture of different configurations of the pressure belt. Manufacturing repeatability is necessary so that it is easy to create said configurations and so Dr. Westphal knows he can trust the results. The width and the height were given by our sponsor because that specific size ensures that the aerodynamic effects of the system are minimized. The Shore 00 Hardness is a standardized metric for flexibility. Keeping that specification around 40 will make sure the belt can conform well to a body without becoming too elastic. Finally, surface roughness is specified so that the surface will not trip the flow from laminar to turbulent.

Measurement method for each specification:

- The number of pressure ports can simply be counted.
- The size of the ports can be measured by stainless steel tubing as a gauge.

- The connections to standard pressure tubing can be tested by performing a leak test to see if the connections are viable and leak-free.
- The pressure accuracy and precision can be measured by using the data obtained from our product and comparing that to known data from previously wind tunnel tested airfoils at the Cal Poly campus.
- The overall cost can be measured by adding up all expenses and keeping track of all purchases made throughout the duration of the project.
- The width of the belt can be measured using calipers.
- The manufacturing repeatability can be measured by observing if the team is able to recreate the product at least twice with minimal issues.
- The Shore hardness of the belt can be measured using a durometer.
- The installation time can be accounted for by doing a trial run and seeing how long it takes to install the product.
- The height of the belt can be measured using micrometers.
- The surface roughness can be measured using a profile gauge.

The pressure accuracy and precision measurements are considered high risk because this is the most important aspect of the entire project. If the measurements are not accurate, the product is practically useless. Manufacturing repeatability is also high risk because methods for pressure distribution measurements already exist. If we are unable to efficiently create this product, the client might choose the previous product over the one we design.

4.0 Concept Design

4.1 - Design Ideation Process

Dr. Westphal has provided us with a restrictive form factor and interfacing specifications. This means that the basic shape and many of the necessary properties of the belt are fixed. Our ideation primarily generated ideas for manufacturing belts that were thin enough, while maintaining the integrity of the vias. Our initial brainstorming sessions produced many results; however, several of these ideas were similar to each other, or sprung from previous ideas with slight tweaks.

The first group of ideas involved taking some pre-made tubing material and retrofitting it into a belt. This might include acrylic plumbing, straws, needles, or metal tubing, bound together to form a long array of vias, with holes punched in the top to act as ports.

Our second group of ideas was to put modular pressure sensors directly on the wing. We considered placing electric pressure transducers, pressure diaphragms, or flowmeters directly on the wing and routing the data electrically to the BLDS.

The third of these groups was some type of cast. We came up with many different casting and molding materials that we thought would work, such as silicone, hot glue, UV resin, clay, or PLA.

The last group of ideas all had some type of precision computer numerical manufacturing technique, such as SLA resin printing, or laser cutting or CNC machining rubber. There were also miscellaneous ideas that did not fit into these categories, such as applying a pressure-sensitive paint to the wing. The complete list of our preliminary ideas is attached in Appendix D.

We pared down each of these groups to their best, most feasible design and compared those against each other. Out of our brainstorming session, our four most feasible designs were a low-profile belt cast from some rubber/flexible resin, a “gang of tubes” design made from off the shelf tubing, a 3D SLA printed rubber belt, and an array of miniature electronic pressure transducers routed directly to the DAQ on the BLDS. We then moved forward with these four ideas, described in finer detail below, and analyzed them with more detailed design matrices to determine our optimal design. We also compared them against the currently available device, the sweated copper tube belt. We used the copper tube as our reference datum.

4.2 - Top Concept Sketches

Figure 4.1 Copper sweated tubes (existing design)

Copper sweated tubes shown in Figure 4.1 are a previously created design that would use rigid copper tubing sweated together, attached to the wing. Holes would be drilled into the tubing to be used as pressure ports. The front of the tubes is sealed to prevent air from entering the device. This design is shown in more detail in Figure 2.1.

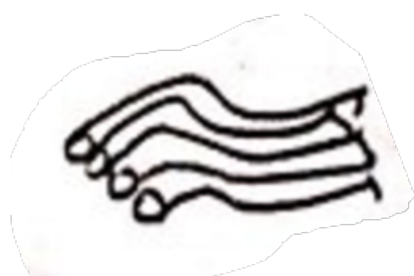


Figure 4.2 Plastic gang of tubes

The plastic gang of tubes seen in Figure 4.2 would use off the shelf plastic tubing to create the pressure vias to connect the belt to the BLDS. Like the copper tubing, holes would be drilled into the tubing to create the static pressure ports. This is difficult to do precisely with the brittle acrylic material, and curved surface.

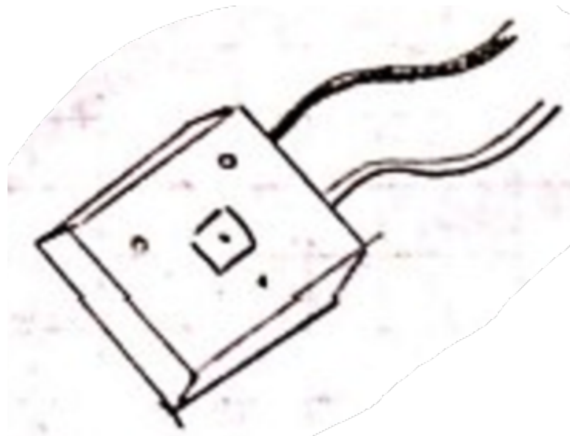


Figure 4.3 Distributed sensors.

By putting small pressure sensors, as seen in Figure 4.3 directly onto the wing, we could take pressure readings without needing pressure vias or other small complex features. This system would interface with the BLDS through an electronic data line and would require a power source and possibly custom developed software.

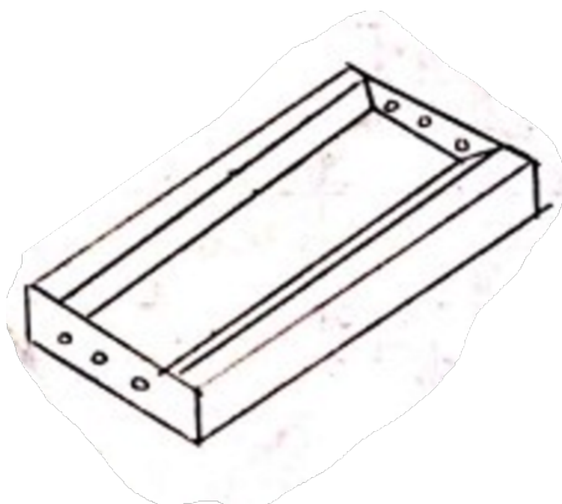


Figure 4.4 Resin Casting Mold

This concept shown in Figure 4.4 involves using 3D printed molds and wires to create a negative of a pressure belt, and then resin or silicone would be cast into the mold to create the pressure belt. Once the part has been cast and demolded, a hole could be punched in the top of the belt to act as a pressure tap at the location of interest for measurement. The holes facing the leading edge will need to be filled.

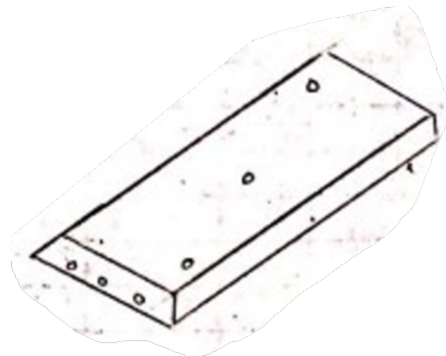


Figure 4.5 3D printed belt

A 3D printed belt, shown in Figure 4.5, would be created using either SLA or PolyJet printing of a flexible substance. This would allow for the relatively complex internal features to be manufactured, which would not be possible with traditional 3D print methods. The form factor of the belt would be virtually identical to the resin-cast device.

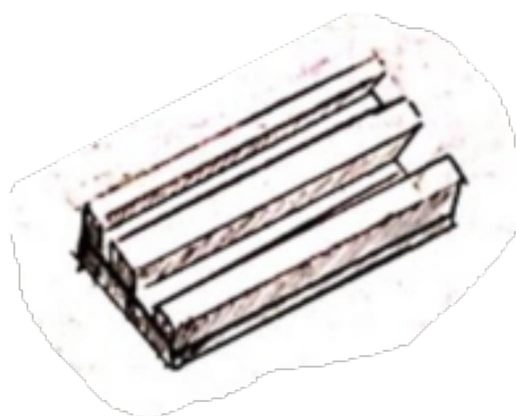


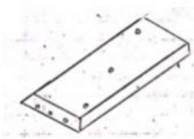
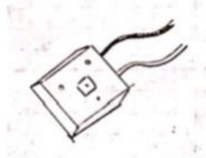
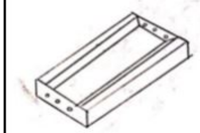
Figure 4.6 Laser cutting

Figure 4.6 shows how a laser cutter could be used to cut vias into a billet of rubber. A sheet of rubber with holes over the vias in desired locations could then be attached to the on top of it. The front would need to be filled for this design as well.

4.3 - Design Process

Throughout the concept design stage, most things seemed reasonably feasible, considering the relative crudeness of the models. This then progressed to the Pugh Matrix, as seen in Appendix C, which allowed for numerical analysis to sort through the existing concepts. When developing the Pugh Matrices, the laser cut vias and sweated tubing were still included for the sake of evaluating as many potential candidates as possible. The Pugh Matrices made it clear that neither of those ideas were not nearly as viable and were filtered out to hone the search to a finer point. The morphological matrix did not lend itself to the project, and the remaining ideas were instead subjected to the final Weighted Decision Matrix shown in Table 4.1.

Table 4.1 Weighted decision matrix

		 3D printing		 Electric Transducer		 Resin Casting		 Gang of Tubes	
Specification	Weight	Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted
Number of pressure ports	15	10	150	10	150	10	150	7	105
Size of pressure ports	15	7	105	10	150	7	105	7	105
Connect to standard pressure tubing	5	6	30	3	15	6	30	7	35
Pressure Accuracy and Precision	6	7	42	9	54	7	42	7	42
Cost	11	5	55	4	44	7	77	6	66
Width of belt	8	7	56	8	64	7	56	5	40
Manufacturing Repeatability	11	6	66	8	88	7	77	9	99
Shore Hardness	1	10	10	10	10	10	10	10	10
Time of installation	3	7	21	9	27	7	21	2	6
Height of belt	8	8	64	10	80	8	64	7	56
Surface roughness	6	9	54	8	48	8	48	2	12
Technical Risk	8	8	64	1	8	7	56	7	56
Supplemental fairing required	3	10	30	4	12	8	24	1	3
Totals:	**100**		**747**		**750**		**760**		**635**

In deciding our final design direction, we analyzed several viable candidates on different ends of the manufacturing spectrum. With respect to the engineering specifications the gang of tubes performed worst, which was expected, as it is the design that the project aims to improve upon.

The gang of tubes performed poorly, because there are known difficulties with producing the ports use to measure the static pressures. The difficulty is that the plastic behaves in a way where it develops burrs that block the pressure vias when a hole is punched through. The plastic tubing itself is difficult to fair, which impacts the accuracy of the data that it measures and makes it challenging to sell as a service to flight instrumentation companies. In addition, after receiving a sample from a manufacture, we noticed that the tubing is not as flexible as we would like. Additionally, we would not be able to use the transfer adhesive to secure it because the diameter of the tubes makes it too tall, and it has less surface area for adhesion (due to the circular cross section of the tubes). The most feasible option to mitigate these concerns would be to make and additional fairing to support the tubes, however that also increases the profile of the body and creates a more time-consuming setup and implementation procedure.

Direct additive manufacturing and casting fall in a similar score ranges to each other, which is unsurprising considering that they both yield the same general end-product, but with different material options and manufacturing challenges. SLA and PolyJet printing are severely inhibited by the inherent bed size of the machine and prove much more costly, considering the printing would have to be outsourced to an independent contractor. There is a certain quality and repeatability guarantee on things such as surface finish and dimensional accuracy that comes with said outsourcing though. The PLA mold can be manufactured once and then used repeatedly, whereas a 3D printed belt must be reprinted for each use, however the 3D print process overall is more repeatable than the cast. Lead time on the fabrication and shipping, as well as their incurred cost, lowers direct printing's overall score. The molding is certainly a more robust direction, considering the mold negative can be fabricated in house and is reusable. Molding does face similar challenges as the direct printing, largely when considering repeatability and plumbing connection.

When looking at the electric sensor design, it proves to be a more, "all or nothing" concept. Whereas mechanical systems can work even when not perfect, electrical systems need all their components to function perfectly for meaningful measurements can be taken. Its key downfall is the technical risk associated with its development, which reduces its score considerably. The hardware on the BLDS is non-adjustable, which creates significant design constraints that we would need to tailor our design to. This makes it a far riskier design to pursue than the others. In addition, an extra fairing would need to be constructed to house the sensors, which makes for an extra step that direct additive manufacturing and casting do not have to worry about.

4.4 - Design Direction Decision and Concept Prototype

We chose the cast pressure belt as our design direction. As previously discussed, though the electronic sensors score highly, we were worried about our ability to effectively implement them within the span of our senior project. As it stands, the team has limited knowledge about electronics, and the technical risk associated with that design outweighs its functional benefits. The cast pressure belt is the best option, and we are much more confident in our ability to design an effective pressure measurement tool which still fulfills all our design specifications using this method.

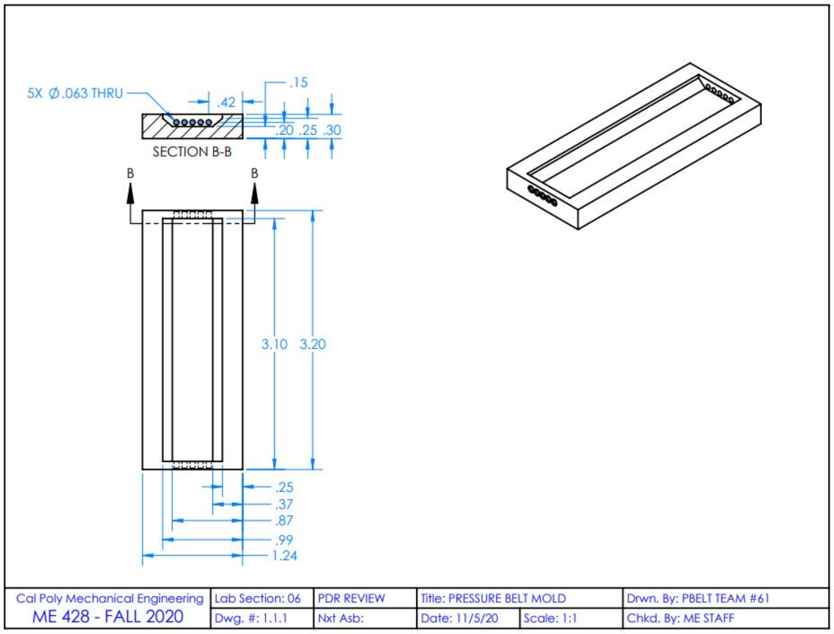


Figure 4.7 Detail drawing and isometric view of casting mold for pressure belt.

Figure 4.8 Casting mold filled with rubber-silicone agent pre-release for feasibility test.

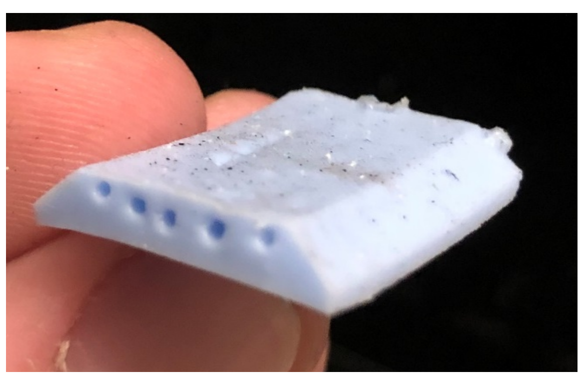


Figure 4.9 Rubber-silicone prototype with vias made by variable diameter music wire inserts.

The pressure belt casting mold functions just as standard molds do, with the negative creating a desired cross-sectional shape. The mold itself is 3D printed using PLA with a 0.4 mm diameter nozzle and ironing on to enhance surface finish and reduce porosity. There are two end-piece molds, that are then connected to a pre-determined number of "middle pieces" in order to develop a full-length mold. The mold pieces are then aligned, bonded together, and sanded to allow for a completely contiguous belt. The holes in the side of the end piece molds allow for rigid inserts to function as removable cores, and create a perfectly unclogged, straight, and dimensionally accurate via. The 2-part casting agent is then mixed, degassed, and poured into the full-length mold, with any potential leakages from the end holes being sealed with putty. The silicone cures for 24 hours and is then removed from the mold. The inserts are made from 0.036" stainless steel hypodermic tubing from McMaster-Carr. This material is highly rigid, which prevents the cores from sagging and contacting the bottom of the mold. A biopsy punch (a tool used in the medical industry to take skin samples) will be used to create the pressure ports on the top of the belt.

The cast vias will ultimately be attached to the BLDS. This could be done using oversized stainless-steel tubing. The interference fit with the silicone belt ensures an airtight fit with the belt. The other end of the tubing can insert into standard vacuum tubing that the BLDS uses. We must size our via diameters such that the size of the BLDS vacuum tubing matches so that the coupler can interface with both.

Our design meets all our necessary functions well. It will be a slight challenge to attach to the wing because silicone is notoriously difficult to adhere to surfaces, however, the 3M transfer adhesive claims to bond to silicone with a 4psi lap shear strength. Further testing will confirm the efficacy of the adhesive.

The stainless-steel couplings fulfil the function of interfacing with the BLDS and allow the pressure belt vias to be plumbed to the pressure transducers and onboard DAQ. Because the pressure ports in the belt are punched into the belt after the molding process, their location longitudinally along the belt can be adjusted as necessary, so we can effectively route pressures from any location on along the length of the belt to the BLDS with this system.

The height of the system will remain under 0.15", and if the mold is properly smoothed and sanded, the surface finish of the upper surface will remain smooth, so we have no concerns about it interfering significantly with the boundary layer. Time permitting, we would like to do additional CFD testing and wind tunnel calibration to confirm that this is the case, but any alternative solution would surely be just as intrusive to the boundary layer.

During an early prototype, preparing the cast took about a half an hour, plus the lead time to print the mold. The cast could easily be performed by one person so we are confident our sponsor could produce reliable belts quickly with minimal effort.

4.5 - Preliminary Analysis

Our preliminary analysis focused on the drag produced by a belt and comparing it to the strength of the transfer adhesive that would be used to attach the belt to the wing. This analysis told us if our adhesive was strong enough to hold the belt to the wing during a flight. As a worst-case scenario, we chose the dimensions of the belt to be as large as possible, given the maximum dimensions given by Dr. Westphal.

After discussion with our sponsor, we were advised to include situations where the belt is not perpendicular to the flow, which significantly increases the drag force. These calculations are shown in more detail in section 5.0 Final Design, and in Appendix E.

4.6 - Current risks, challenges, unknowns, and next steps

There are a few risks associated with the current design. As detailed in the Design Hazard Checklist in Appendix F, sharp edges may be present in the manufacturing process of the casting. Cores that are being used as negatives for the cast may be sharply pointed on the ends and are especially dangerous when under tension. To account for this, we will be wearing gloves and eye protection when working with the mold. Other safety hazards may include the risks involved with certain casting materials and the use of a vacuum chamber for the casting. Both may be accounted for by following the respective safety guidelines. When deciding on a final casting material, we must also account for the device being exposed to harsh environment conditions associated with being mounted on an aircraft wing.

A particular challenge associated with the current design is how to properly connect the numerous mold segments. Some current ideas to solve this problem include the use of a fixture or sealant to attach the molding together or making another casting surrounding the two smaller pieces and thus sealing them together. On our first attempts, casting over a long distance (up to a few feet) proved to be a challenge that needs to be addressed as the project progresses. Another challenge is deciding how the belt will connect to the preexisting BLDS. With the current design, it is not possible to use standardized plastic couplings because the hole is too small. We will need to design our own couplings. However, more analysis and testing will need to be done to make a final decision on this issue.

5.0 Final Design

5.1 - Design at Critical Design Review

The overall final design can be considered in two stages, the first of which is the mold. The mold itself is printed and sanded on the surfaces that silicone will come into contact, to improve surface finish and ease the de-molding process. The mold also has a trapezoidal cross section to reduce the resultant belt's impact on the flow field. The number of holes in the mold is adjustable in CAD, allowing for easy configuration changes (i.e., between 5 via channels, and 8 via channels). The mold depth is 0.15”, which allows the height of the resultant belt stay within specifications.

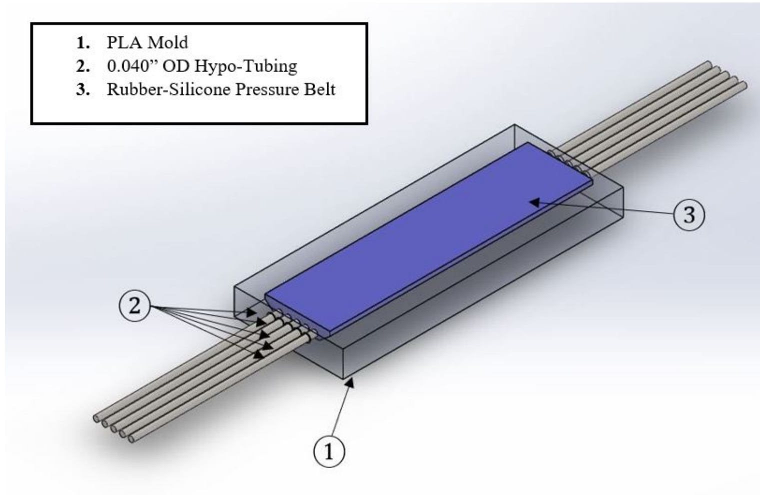


Figure 5.1 5-via belt mold assembly after rubber-silicone pour with insertable cores left in.

The belt itself, after demolding, is the true final product. The profile will mirror the mold specifications within acceptable tolerances. The insertable cores guarantee the vias remain clear and true to their dimensions. The belt's shore hardness allows for flexible installs in hard-to-reach or compact areas without blocking flow. The low profile also experiences a lower drag force, allowing us to use a light-duty transfer adhesive for installs, dramatically reducing setup and tear-down time. Finally, the silicone material will contract around any inserted hose barbs, ensuring that connections are made with no leaks.

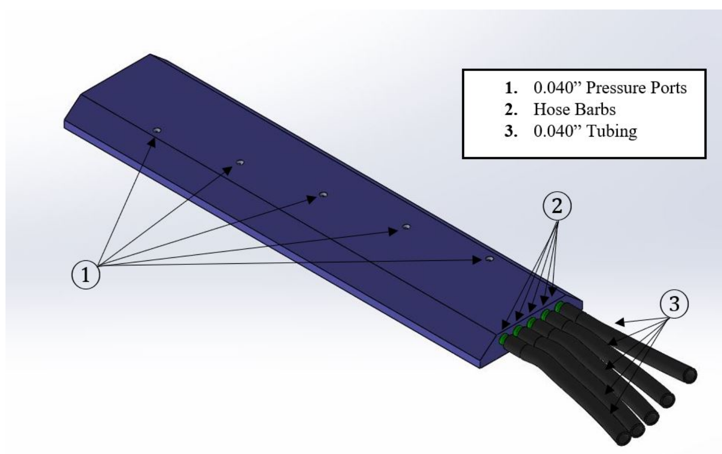


Figure 5.2 Test prototype belt, with pressure ports, hose barbs, and attached 0.040" tubing.

The three major subsystems of the design are the mold, belt, and the couplings connecting the belt to the BLDS. The mold is designed through SolidWorks and made through 3D printing. This piece, as documented in Figure 5.1 and in Appendix H, will have 5 holes on each end for the core inserts and be used for casting the silicone rubber. The belt is the product of pouring a silicone rubber mixture into the mold and allowing it to cure. This belt is detailed in Figure 5.2 and Appendix H. Thus, the silicone belt will have the corresponding holes from the cores and be the size dictated by the internal cavity of the mold. Finally, the couplings can be purchased from a manufacturer. These will be used to connect the ends of the mold vias to the BLDS. The couplings have yet to be assigned a final selection, as they can only be selected when connection to the BLDS is an option. As such no drawing is included, considering the only specification that is certain is their size, 0.040” OD. The total cost up-front purchasing cost of the belt is $238.39.

Table 5.1 Material Cost Breakdown

Material	Cost Per Unit	Quantity	Total Cost
PLA 3D Printer Filament, 1kg spool, 1.75 mm, White	$15.14	1	$15.14
0.042" 304 Stainless Steel Tubing, 3ft	$15.14	8	$121.12
Epoxy Glue	$17.58	1	$17.58
SORTA-Clear 40 Silicone Trial Unit	$40.87	1	$40.87
Biopsy punch	$30.00	1	$30.00
Couplings	$1.71	8	$13.68
Total	-	-	$238.39

The pressure belt would be mounted to a surface and faced toward oncoming flow. The tubing runs to an external system, in this case the BLDS, with pressure transducers. The pressure ports located on the top surface are arranged at different lengths and communicate the static pressures to the pressure transducers accordingly as the flow runs over it. The system’s low-profile means that the oncoming flow will not be meaningfully perturbed and maintains the data such that it is an acceptable alternative to pre-installed pressure taps.

Figure 5.3 Structural Prototype of a 6" belt

5.2 - Design Changes and Challenges after Initial Structural Prototype

The structural prototype proved promising but was only tested at 6” of belt length with 5 vias. The cores were not too challenging to remove and produced a visually perfect 0.040” cylindrical channel. There was concern that the cores would sag, but this was not an issue at the small, tested length. No leakage was observed, and the cores fit tightly into the 3D printed mold. The heat gun removed a considerable amount of air bubbles on its own, but the clear silicone showed that there are still small air voids in the belt. These are not necessarily harmful, and further testing will be done to verify this. The silicone will have vacuum pulled on it in the next iteration to see its effect on the number of voids. The next length will also be tested at 12”, to verify that the hypo tubing will not bow at higher belt-lengths. This extra length will also verify that the cores are still removable, and do not get stuck due to the increased adhesive force. Finally, PLA proved to be a very viable mold material, and was not an issue in terms of either porosity or surface finish.

The pressure belt prototype is at least as viable, due to the low-profile and material flexibility. Silicone allows for the pressure belt to be installed on virtually any surface, while still maintaining its via structure. In addition, the use of 3D printed molds allows for uniform and customizable cross-sections, making the production of these belts far easier than the sweated copper tubing first seen. When analyzed to ensure that the light-duty 3M adhesive can sufficiently hold the belt in place on a fuselage, the belt proved itself incredibly safe. In the worst conditions feasible, (15 degrees of misalignment, 400 psf of dynamic pressure, weight considered, 50% adhesive cure, and a drag coefficient of 0.5) the belt maintained a factor of safety of above 27, as seen in Figure 5.3. As per Dr. Westphal, anything above a safety factor of 6 is considered a non-issue, so 27 is exceptionally good. Finally, the structural prototype’s successes suggests that the manufacturing direction is viable and should be pursued for full length belts. If the properties translate well, the vias will be perfectly clear and well under the maximum outer diameter. The material properties of the prototype suit the required flexibility well, and the height of this belt was already within the envelope. The prospects for a longer belt while translating these specifications is promising.

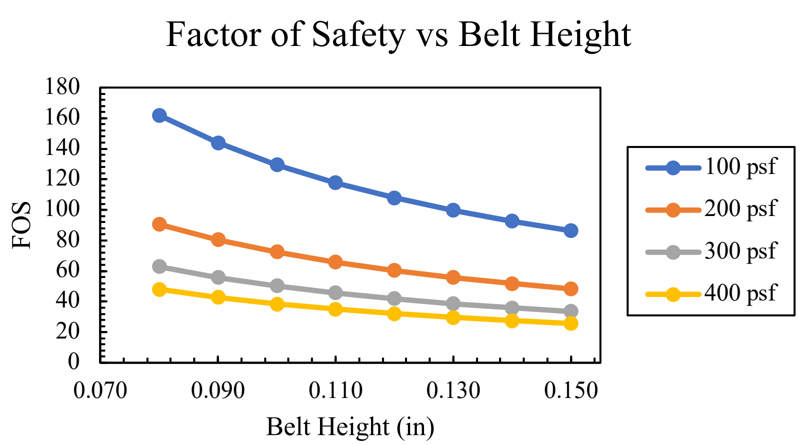


Figure 5.4. Factors of Safety vs. Belt Height and Dynamic Pressure

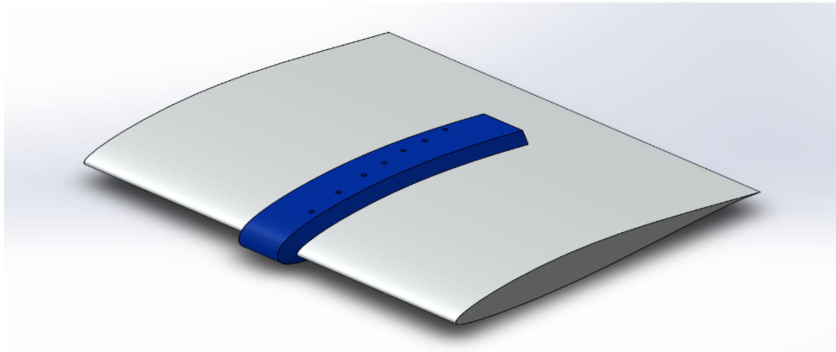


Figure 5.5 Implementation of the belt on an airfoil

5.3 - Design Changes leading to Final Design

More than anything else, our approach to this project was very iterative. We had proved the feasibility of our casting technique late in the first quarter, well before the expected timeline. Because repeatability and ease of manufacturing was such a crucial part of the project, the remainder of our time was spent iterating and honing our process to produce the optimal final product to Dr. Westphal. On a macroscopic scale, everything remained the same. But many of the finer details of our mold set up and design, and our manufacturing process were altered to produce better results.

The primary issue that remained after our structural prototype was the amount of air bubbles still encapsulated in the belt. This was causing some vias to leak and we were not able to consistently pass all our tests. Additionally, the bubbles caused surface defects and made it difficult to punch ports in the top of the belt. To combat this problem, we added a vacuum process to our procedure. The vacuum process takes place after mixing the 2-part silicone is mixed, as the mixing process is what incorporates most of the bubbles. This takes care of most of the bubbles, however some remained after pouring the mix into the mold. To get rid of these remaining bubbles, originally, we built a vacuum chamber out of PVC piping that the mold could slide into after we had poured the silicone in it. However, we realized that this process was causing more problems than it was worth because we could no longer see the status of the belt as we pulled a vacuum on it. So instead, we decided to only pull a vacuum on the mix once, after it was mixed, and use a toothpick or similar needle-like pick to remove any visible bubbles after we poured. A more detailed description of the degassing process is outlined in our manufacturing plan section (Section 6.0).

Another design change we made was to the way to cores inserted into the mold. We had problems with the durability of our cores and were having to replace them after 2-3 belts. We had intended to make these cores reusable to keep the cost of production down. Any slight bending to the cores can cause them to touch each other or the bottom of the mold, leading to leaks in the belt. Inserting the cores through the holes in the mold proved difficult and often lead to axial forces in the cores that caused slight bending or buckling. To combat this, we altered the mold design to have V-slots instead of holes, which the cores could slip into, rather than being pressed through.

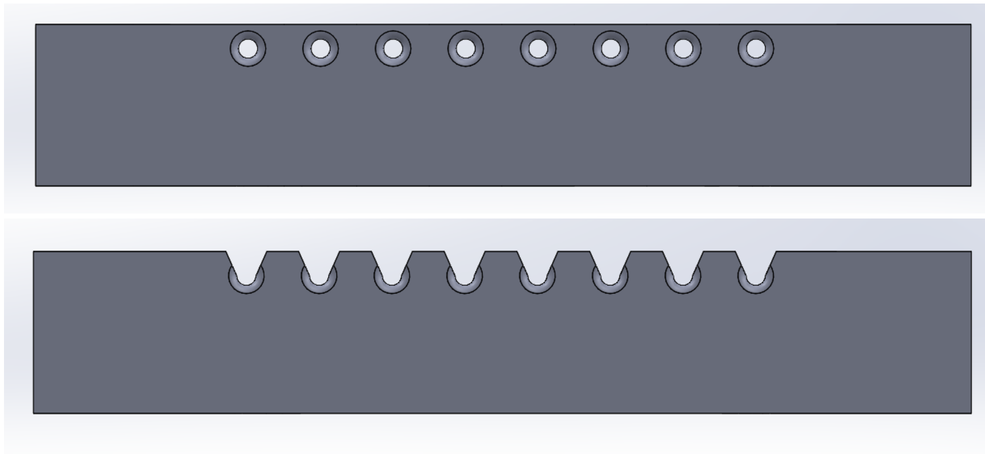


Figure 5.6 Comparison between old mold design with holes and new design with V-Slots

Additionally, due to problems removing the cores from longer lengths of belts, we moved to create 10.5” belt segments that could then be connected together using the same stainless-steel couplings we used to route to the BLDS. This allows Dr. Westphal to maintain flexible lengths. There are more details on how we combatted the core removal problem outlined in the manufacturing chapter (Section 6.0).

Over the course of our iterations, our mold shape changed slightly from one configuration to the next. These changes included: spreading the vias out more and making a wider belt to help keep the vias from bridging to each other, making the depth of the mold smaller to produce a thinner belt, and moving the vias towards the bottom surface of the mold. The via core diameter was also changed to 0.036” to create a snug interference fit with the tubing.

All these changes allowed us to get to a point where we can consistently produce satisfactory belt segments that do not leak or have any other defects.

6.0 Manufacturing

The manufacturing process can be broken down into two segments, the mold/casting process, and the assembly process.

6.1 - Silicone Molding Process

The mold is 3D printed out of extruded PLA plastic. The filament can be sourced from a host of suppliers. The technical specifications of the 3D print are not critical for the outcome of the final part, i.e., use whatever you are comfortable with and have had success within the past, so long as you can get the resolution necessary for the holes. In our case, the part was sliced using Cura, with a layer height of 0.07mm in order to offer sufficient dimensional accuracy for the holes in the mold. Hatchbox 1.75mm engineering grade white filament was used due to its tolerance range (±0.03 mm). The print’s major dimensions follow the CAD net shape specifications closely, with the overall length being consistently within ±0.010”, and the hole spacing being within ± 0.005”.

Since we used a 3D printing process and we were limited by our print bed size, the molds had to be printed in >6” segments. End segments have 3 walls (capped on one end), while intermediate segments only have the 2 longitudinally oriented walls with openings on either end. The segments fit together through registration pins that keep the part axially aligned. The mold segments can be lightly adhered with a two-part epoxy putty to fill and smooth any gaps between the segments. This putty, “Green Stuff” can be sanded after curing to make the bonded surfaces flush with one another. We found that past 15”, the cores became difficult to pull out of the silicone, but future iteration might allow for longer belts to be produced, and more mold segments to be linked together.

The cores, made of 0.036” stainless steel hypo-tubing from McMaster-Carr, must be lubricated to allows them to release from the cured silicone. To do this, we took some petroleum jelly on our fingers and applied it liberally to the cores, rubbing it down the length so that the surface was coated. Then we took a clean, dry towel or paper napkin to wipe away all excess petroleum jelly. This results in a very thin, imperceptible layer of petroleum jelly. It is important to minimize the amount of lubrication on the cores as excess could contaminate the silicone or clog the vias. We did not allow the lubricated cores to touch un-clean surfaces to minimize debris from sticking to the cores and being encapsulated in the final belt. We either inserted the cores directly into the mold after lubrication or placed them on a clean towel.

Originally, our mold was printed with 0.040” holes on either end of the belt. These holes could be filed to let the cores insert snugly. However, we found that getting the cores through the hole was difficult and often led to the cores bending and becoming unusable. To combat this, we changed our 3D print file to have V-slots instead of holes. With this design, the cores can be loaded from the top and snap right into place from above, without ever being loaded axially. The gaps in the mold caused by the V-slots can be sealed with putty to prevent leaks. We had to occasionally separate cores that touched each other in the mold; if this remains a problem, the mold can be printed with the V-slots farther apart.

Figure 6.1 A 6" segment of the mold with hypo-tube cores installed.

To cast the part, we use the Sorta-Clear 40 durometer silicone rubber (sourced direct from manufacturer.) The rubber comes as a two-part compound which needs to be mixed and subsequently degassed to remove any air bubbles introduced during the mixing process. The silicone has a 10:1 ratio of part A to part B by mass. We found that we would use 5 grams of part A per linear inch of belt for our mold configuration (this may change if the shape of the belt is changed). In general, since silicone has a specific weight of 1.06, we found that mixing 1.15g of part A per cm^3 of belt was a good starting point.

Due to shop-access issues, we retrofitted a vacuum chamber using a vacuum pump and an airtight mason jar with a vacuum tube barb-coupler. The Sorta-Clear manufacturer recommends pulling a 29 inHg vacuum for 2-3 minutes. If a proper vacuum is achieved, the mixture foams up with an airy layer on top. Once all gas is removed, this layer collapses, indicating the mixture is sufficiently degassed. When setting up the vacuum chamber, allow enough clearance between the top of the jar and the surface of the mixture to keep this foam-layer (typically about 1.5" tall) from contacting the vacuum port and clogging the tubes. It is important to not let it degas for too long as the pot life is only 60 minutes. We typically ran the vacuum for 7-10 minutes.

Figure 6.2 Vacuum degassing chamber made from a mason jar with a vacuum barb in the top.

Once degassed, the silicone can be poured up to the fill line of the mold. The silicone is very viscous and does not flow efficiently across the full cast, so we must pour evenly across the length of the mold. We used a heat gun to bring any remaining air bubbles to the surface and pop them but were careful not to get it too close to the mold as the heat can cause the PLA to warp. Typically, we would keep the tip of the gun 2 feet away from the part and keep our use to less than 10 seconds at a time, moving in quick back-and-forth strokes over the entire part. The heat gun also helps "sets" the very top layer of silicone, which keeps the any remaining voids from breaching the surface of the belt.

Figure 6.3 Pouring the viscous silicone mixture into the mold.

The belt cures for about 18 hours, depending on the ambient temperature. After the belt is fully cured, the cores are removed gently so as not to bend them, and the silicone releases easily from the PLA mold. At this point the casting process is complete and the assembly/post-processing stage can begin.

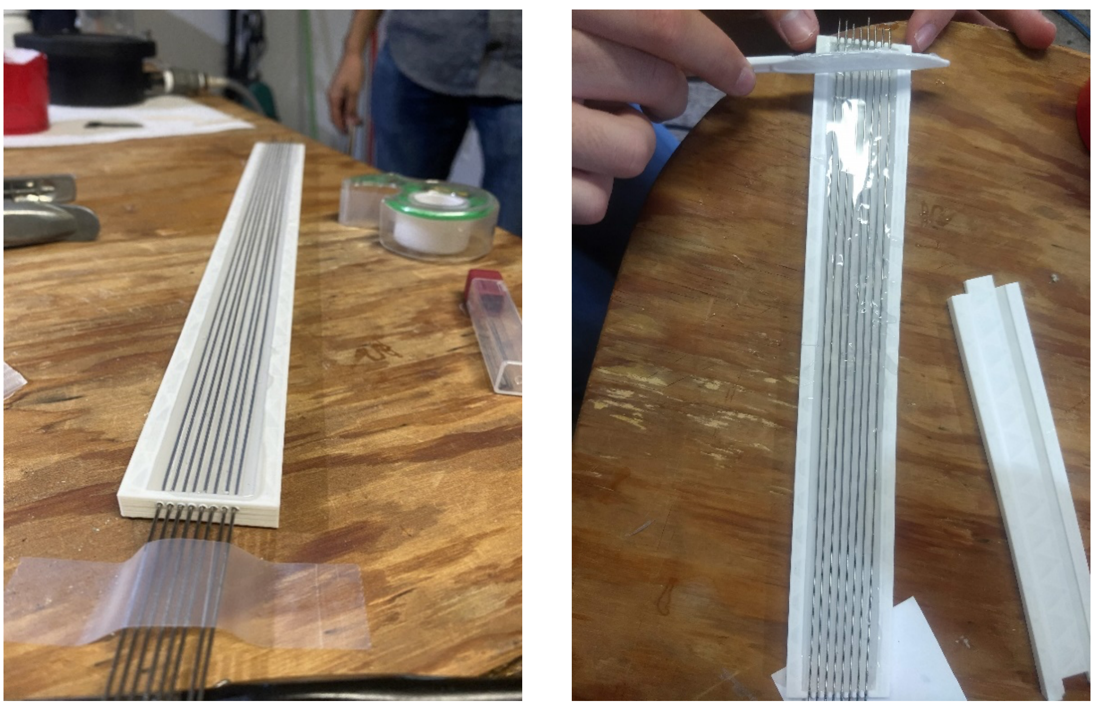


Figure 6.4 A segment of the mold with hypo-tube cores installed after silicone pour.

6.2 - Assembly, Installation and Postprocessing

Any flashing that occurs on the edges of the bottom of the belt can be trimmed easily with a knife. The front end of the vias is sealed by painting more silicone mixture on to the front end of the belt.

A vacuum hand pump can be used on the other end of the via to gently pull the silicone into the via. To maintain a pristine frontal area, we cut the first ¼” of the belt flush. The biopsy punch cuts pressure ports into the top surface of the belt wherever needed. Finally, the stainless-steel couplings are pressed into the end of the belt and routed to the tubing of the BLDS.

If we want to measure on a system longer than one belt length, instead of sealing the front end the belt, we use the stainless-steel tubing to link two belts together. Assuming an airtight fit is achieved, this gives us the ability to make a belt of any length.

The stainless-steel couplings are made by taking 0.042” hypo-tubing and cutting it with a Dremel cut-off wheel into ½” lengths. The edges might need to be sanded to break the sharp edges and ensure the tubing is not obstructed by a burr.

To adhere the belt to the surface of a body, we applied isopropyl alcohol to the surface to remove any dust or oils. The transfer adhesive, which comes in a roll, can be cut to the length of the belt and applied to the surface once the alcohol evaporates. Then we placed the belt over the top of the adhesive and applied light pressure to the top of it for 30seconds. Once the belt was secured with transfer adhesive, we placed aluminum “speed-tape” around the edges of the body to prevent air from getting under the belt and lifting it off the body.

6.3 - Challenges, Future Recommendations and Lessons Learned

Some of the challenges the team encountered included eliminating the air bubbles from the silicone molds. This problem was ultimately solved by ensuring that the initial silicone mix is slowly mixed and applying our vacuum and heat-gun process on the mixture. The poured silicone is then visually inspected, and any of the larger bubbles are popped with a toothpick. Other issues included pulling out the cores from longer belts which is remediated with the application of the petroleum jelly on the cores before casting. Reusing the cores also causes some problems as repetitive removal of belts from the cured cast results in slight bending of the hypodermic tubing. Although this bending is very slight, this still renders the cores unusable for our purposes. The cores are an expensive part of our belt, and we did not want them to be a recurring cost. Making the mold with V-slots instead of through-holes minimized bending of the cores and extend their life.

Repair and maintenance are not significant concerns for us, as our sponsor will be receiving all plans and processes for our project. The variable configurability of the mold allows Dr. Westphal to size the belts to his application without needing to print multiple molds.

Some future design iterations could make the belt entirely from a 3D print UV resin process. Unfortunately, the team was unable to find a vendor that could print the belt with the correct material and the correct resolution. Other suggestions could be to repeat this process with a silicone rubber that has a higher hardness which would allow for easier application to any aircraft structure without possibility of stretching. If desired, edits to the SolidWorks file for the mold can be used to fine tune the shape of the belt to minimize boundary layer disturbances, so long as a sufficient draft angle is maintained for easy demolding.

Overall, the price of the materials needed for manufacturing is $423.32 for the materials, most of which will be able to be used for many belts. This value is well under our original budget of $1,000. We sourced our hypodermic tubing from McMaster-Carr and bought our Sorta-Clear silicone straight from the manufacturer. The only other costs were for the 3D printer filament, purchased from Amazon, and some miscellaneous tools and supplies that were not deemed useful.

Table 6.1 Cost summary of project. NOTE: This is *not* the cost of an individual belt.

Item Name	Quantity	Total Cost
Hypodermic Tubing	18 3ft segments	$316.32
3D Printer Filament	1 roll	$15.14
Sorta-Clear Silicone	2.2lb	$40.87
Misc. Costs	N/A	$50.99
TOTAL COSTS	-	**$423.32**

Our major cost has been towards purchasing of core hypodermic tubing. Between release agent experimentation and the delicate nature of the tubes, we have had to replace the cores numerous times. Any slight bend in the core can lead to issues, due to the small size of the belt itself. Moving forward, this should not be as big a cost in producing more belts, as one 2.2lb tub of silicone can make many belts, and the cores can be reused multiple times. Similarly, the mold only needs to be printed once unless a different configuration is desired.

7.0 Design Verification Plan

To verify our design specifications listed in Table 7.2, numerous tests were performed. An overview of each test is detailed in the Design Verification Plan (DVP) in Appendix L. The number of pressure ports was verified with visual inspection. The cost was verified through comprehensive recording of all purchases. The final costs are $432.32. The installation time will have to be discussed with or possibly tested by Dr. Westphal. It will depend heavily on how long he wishes to allow the adhesive to cure.

To verify the geometric form of the belt is within tolerance, we can assume that the belts shape is no larger than the mold it was formed in. Since all our dimensional tolerances are “maximum” values, a mold that fits the specifications will produce a belt within specification. The mold width can be verified with calipers and the length can be measured with a simple straightedged ruler. Gauge pins or calipers were used to test the size of the pressure port holes, the ends of the vias, and the height of the belt. Though, a more critical test was ensuring that the 0.042” tubing inserted into the vias in an airtight manner, which was verified through our leak tests (see below).

Manufacturing repeatability was tested through documenting the process of repeating the production and determining if the ease in which it was completed meets Dr. Westphal’s needs.

7.1 - Leak and Flow Tests

To test the belt's ability to translate accurate pressure measurements to the BLDS, or the belt's accuracy and precision, leak and flow tests were performed. In a leak test, each via was sealed on one end with a dental pick and pressurized to -25 inHg gage on the other. This pressure is held for a 5 count, and any pressure loss marks a failure in the test. This test will be based on a pass-fail criterion and assessed at each via. The leak test requires a hand pump, rubber plugs or dental picks to seal one end of the via, and the silicone belt. This testing was repeated, and the results are used to validate each belt that we manufacture. This also tests that our 0.042" couplings are adequate in creating an airtight seal.

Figure 7.1 Pressure belt undergoing leak test.

In the above Figure 7.1, a leak test is being performed. The dental pick is inserted into a port to seal off the entire via. As can be seen in the picture, the via is holding vacuum, showing that the via does not have any leaks.

Another test to verify the function of the belt is a flow test. This can be performed by running air through each individual via to check that the flow of air can move through the vias unobstructed and at approximately the same rate. Like the leak test, the hand pump is used, however, pressure loss is the success criteria this time. Any blockages in the vias will prevent the air from vacating the space and the pressure in the belt will hold steady, instead of equilibrating. This test will be based on a pass-fail criterion if the air can move through without encountering any blockages.

Figure 7.2 Flow test being performed on the belt.

In the test shown above, nothing is used to block the via. The hand pump pulls a temporary vacuum on the belt, but the belt cannot hold pressure for long and soon returns to atmospheric pressure. This then indicates that the via does not have any obstructions in it. Combined with the leak test, these two tests show that flow only has one route through the port.

Visual inspection tests for the possible voids or air bubbles in the silicone mold were executed. This pass-fail test verified that the voids would not cause any bridging between the two vias, which could lead to leakage, or any additional surface roughness on the outside of the mold. Additionally, the surface roughness was visually inspected to ensure that there were no obvious obstructions to the flow profile over the belt. Because of the small size of the belt, only extreme amounts of surface roughness would have any meaningful effect on the flow profile. Moreover, the correct shore hardness of the belt is ensured by the manufacturing company from which the silicone was purchased.

7.2 - Wind Tunnel Testing

One of the most important tests is the using the pressure belt to obtain pressure data on an airfoil in the wind tunnel and comparing the belt's data to known data. This test setup is shown below in Figure 7.3.

Figure 7.3 Test setup for wind tunnel test.

For this test, the belt is attached to a test airfoil that has pressure ports embedded in the wing itself. In the wind tunnel, we compared the coefficient of pressure, C_p, derived from measurements using the belt to the C_p from the wing itself to see if the data matched up between the two at the same location on the wing. The C_p was defined as:

$$C_\rho = \frac{P_x - P_0}{P_{dyn} - P_0}$$

Where:

P_x is the measured pressure.

P_0 is an offsetting pressure based on the error inherent to the transducer measurement.

P_{dyn} is the dynamic pressure in the wind tunnel (measured with respect to the static pressure outside the wind tunnel).

We were able to run this test for two different angles of attack with a windspeed of 70 mph. The results are summarized in the tables and figures below. Ports are numbered from leading edge to trailing edge. The uncertainty for the values comes from the propagation of the measurement uncertainty of the pressure transducer and voltmeter we used to record our data.

Table 7.1 Coefficient of pressure, C_p measurements for a -0.5° angle of attack. C_p values are ±0.015.

Port #	C_p (Belt)	C_p (Foil)	% Difference
1	-0.26	-0.16	67.2
2	-0.30	-0.33	-8.6
3	-0.30	-0.32	-4.5
4	-0.25	-0.27	-8.6
5	-0.17	-0.22	-23.4
6	-0.14	-0.18	-21.6
7	-0.13	-0.14	-6.5
8	-0.11	-0.12	-3.3

Table 7.2 Coefficient of pressure, C_p measurements for a 5.2° angle of attack. C_p values are ±0.029.

Port #	C_p (Belt)	C_p (Foil)	% Difference
1	-1.32	-1.56	-15.7
2	-0.81	-0.98	-17.3
3	-0.65	-0.69	-6.8
4	-0.48	-0.53	-9.4
5	-0.33	-0.41	-19.7
6	-0.26	-0.31	-15.2
7	-0.20	-0.22	-9.8
8	-0.16	-0.19	-13.1

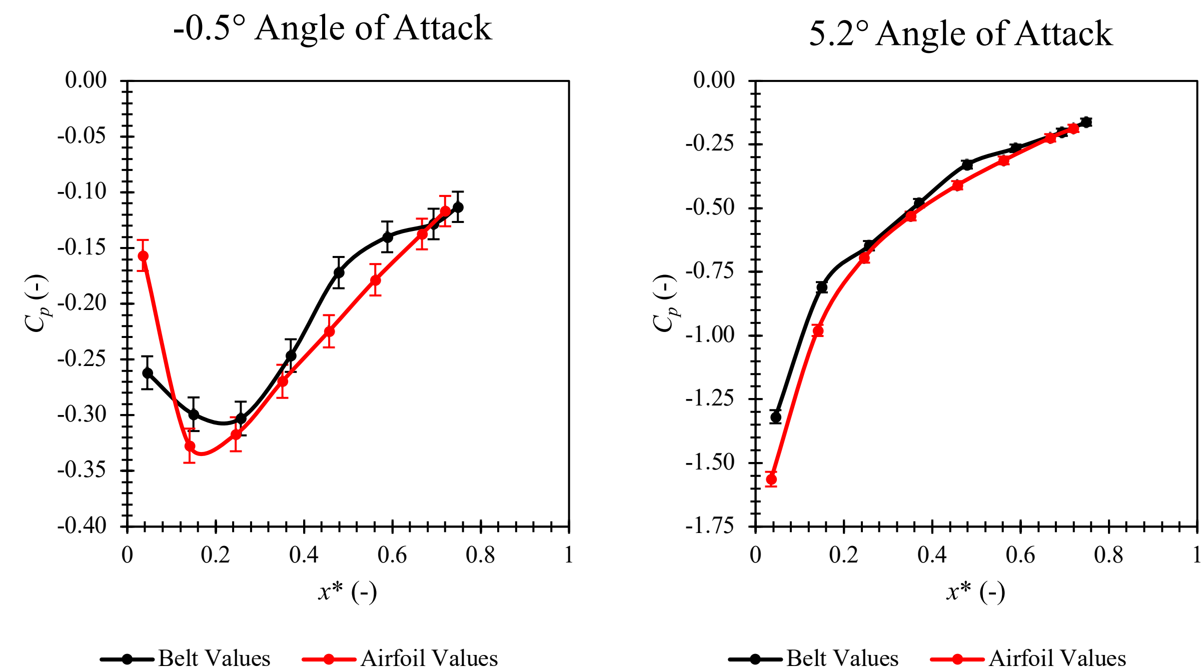


Figure 7.4 Comparison between coefficient of pressure measurements, C_p, taken with our belt and the airfoil's ports at different distances from the leading edge of a NACA-0012.

The results show decent agreement especially further along the airfoil profile. It seems port 5 on the belt specifically had some measurement issues because its reading is significantly higher than the expected value at that point for both cases. Recall that the mold we used to make the belt is made of two separately printed mold segments that are then bonded together. When we perform our silicone cast, the joint between the two mold segments creates a slight surface imperfection in the belt. Port 5 was located just a few millimeters upstream from this imperfection, and port 6 was about a half-inch downstream of it. This is likely the cause for the faulty data at those two ports.

The data shows the most discrepancy at the leading edge, which was expected. At the leading edge, the belt dramatically changes the profile and geometry of the airfoil, whereas farther down the chord, the belt and the airfoil follow the same path and are more perfectly parallel. Additionally, the ports near the leading edge might not be perfectly orthogonal to the flow, causing some stagnation effects to be measured, rather than a pure static pressure measurement.

The error is less than 25% at all locations except port 1, and the overall trend and behavior of the plots is correct. We would certainly like the difference to be less than it is but recognize that the ratio of airfoil thickness to belt thickness is much higher than we would see on a real flight test, which we believe is influencing our results. Also, the ports in the belt and the ports in the airfoil do not line up perfectly, with some ports having a >0.15” difference in x-location. Therefore, we did not expect the ports to have perfect correspondence. Overall, we are satisfied with the results and think it provides strong efficacy for the belt, and the agreement should improve with subsequent iteration.

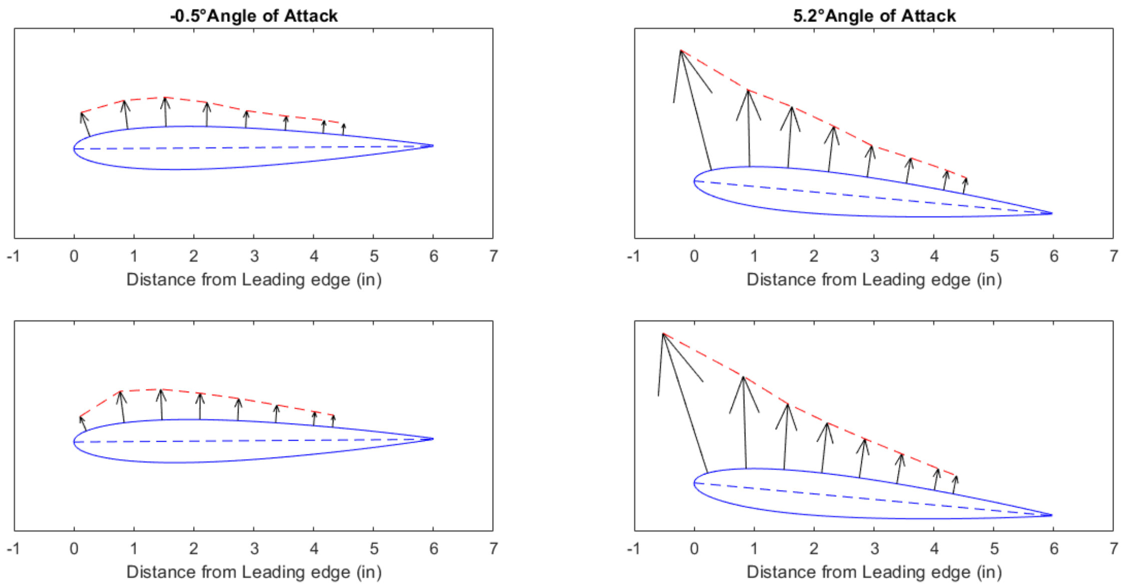


Figure 7.5 Pressure distribution captured with belt (upper) and airfoil ports (lower).

We want to thank our sponsor, and coordinator for the fluids lab, Russel Westphal for providing us with the NACA-0012 Airfoil, allowing us access to the fluids wind tunnel and for putting in extra work to ensure the environment was safe and compliant with school's COVID-19 guidelines.

7.3 - Adhesive Strength Verification

Another important test we performed was the adhesive test. The test was necessary to ensure that the adhesive rating provided by 3M for their transfer adhesive was applicable to silicone-aluminum interface. 3M rates their belt at 4 psi shear strength, but silicone is a notoriously difficult material to adhere. Additionally, this allows us to better asses our biggest design safety hazard – the danger of the belt falling off the airplane mid-flight.

The test was completed by applying a 2" length of 3M transfer adhesive to the bottom of a pressure belt prototype and attaching it to a piece of as-rolled sheet metal aluminum which had been cleaned with isopropyl alcohol. Pressure was applied to the belt for 30 seconds. A fish scale was then attached to the prototype with a spring-loaded clamp and pulled parallel to the surface until either the clamp pulled off the belt, or the adhesive yielded. The force at the yield point was noted.

Figure 7.6. Adhesive test setup

In the above Figure 7.6, from left to right, there is the aluminum plate, a small section of belt, a clamp, and then hidden in the hands a small fishing scale. We recorded the yield force, and then used this force and the transfer adhesive area to get a shear stress. We performed uncertainty propagation and statistics to then get an uncertainty on our shear stress.

In general, the results of the test indicated that the belt would perform with a high factor of safety at the loads we anticipate reaching. The test would consistently end with the clamp sliding off the belt, giving us a "adhesive yield load" of 2.71 ± 0.90 psi at 90% confidence. For a breakdown of the data collected and uncertainty analysis associated with this test, see Appendix L. While this is a wide range of loads, because the adhesive itself never failed in that range, we are more than confident in the belt's ability to stay adhered to a wing despite misalignment. As can be seen below in Figure 7.7, even if our adhesive had a strength of 1.5 psi in a case, we would still have a high degree of safety if the pressure belt were misaligned to the airflow over the wing.

The belt will also be held down by aluminum "speed tape" which will prevent air from getting under the belt and help it stay in place.

Our conclusions from this test are that our belt will remain adhered to an aircraft body with high degree of safety. This reduces our concern of "parts falling off aircraft" (PFOA), which was a major design hazard for our belt.

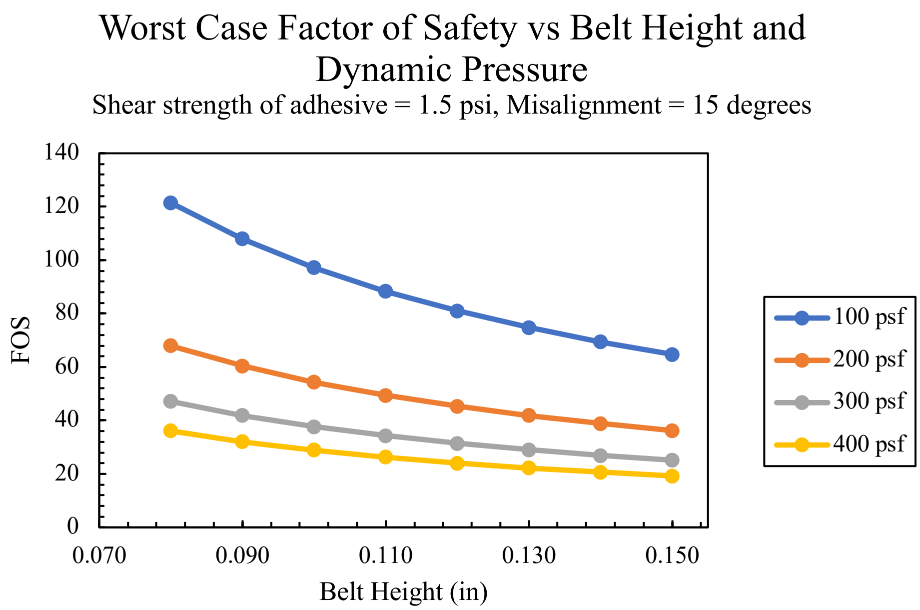


Figure 7.7 Factor of safety graph for the pressure belt at a worst-case adhesive strength.

8.0 Project Management

Overall, the team was successful at following the general design process and creating a successful design. The final design was tested and shows promise to be fully functional. There were many successes throughout the project such as the multiple iterations of the casted belt and the numerous testing procedures. Because this project was fairly matured at the start of the year with extensive research and preliminary testing, some of the administrative tasks at the beginning of the project were not as productive. For example, much of the ideation was completed before the project began so going through this process seemed repetitive. Unfortunately, these types of tasks seemed to get in the way of starting testing sooner. Furthermore, this overall process illustrated the importance of testing as quickly as possible which we would incorporate into any future design projects.

Utilizing the different files that easily summarized many distinct aspects of the project such as the bill of materials, risk assessment, test procedures, and Gantt Chart helped the team regularly document the design's progress. Continued documentation is an important aspect of the design process and something that we will do in the future. Regular deadlines such as weekly meetings and quarterly reports also helped keep the team on track. The general layout of the project scheduling can be found on the Gantt Chart in Appendix B.

9.0 Conclusion

The project attempted to design and manufacture a pressure measurement device that complements and augments the current BLDS that can be more efficiently manufactured and installed than current products. This was a complete success, considering that the device not only passed the technical specifications, but also delivered incredibly accurate data for such a short run. The device itself stayed well within the size envelope provided, which allows transfer adhesive to be used for the installation of the belt. Consequently, the installation procedure was streamlined immensely, making the belt user-friendly. In addition, the manufacturing process for the belt itself was iterated so many times that belts are now able to be produced quickly and repeatably. This process was also re-designed to allow for the only consistent cost to be the silicone needed for each belt, as the mold and insertable cores are both re-usable. The belt being translucent allows for visual checks to look for any blockages or tears, while also being able to see any obvious voids or air bubbles developed during the molding process. Finally, the data was outstanding for the final prototype's initial test and leaves further iteration in a particularly advantageous position.

The belt is, however, fragile because of the selected silicone. The low shore hardness results in a very flexible material, but also allows for elongation and tearing during installation. This would be supplemented in future tests by selecting a new silicone rubber in the 60A – 70A range. This would allow for greater durability and rigidity, while still maintaining an air of flexibility. The project also failed to directly print a pressure belt, as the manufacturers were not confident in their ability to print a short run at the spec that the belt demanded.

If revisiting things at the start was an option, we would have started testing belts earlier, as the project was heavily reliant on the process of manufacturing quality belts. The option to start prototyping earlier would have also been helpful, as iteration of the belt molds was the main progression method.

Although we were overall satisfied with the results of our project over the year, there are steps that can be taken to further the project goals. We would recommend continuing iteration of the final design while utilizing a more durable silicone with a higher hardness. This should greatly improve the overall design and possibly eliminate sources of error such as leaks create from post-processing or handling. Additional testing especially in the wind tunnel would also be beneficial. Unfortunately, the team was only able to access the wind tunnel during the last few weeks of the project. Thus, only one successful airfoil test was completed. Although the preliminary results of this test looked promising, continued tests with new iterations of the belt would provide more valuable insights into the verification of the belt.

10.0 References

3M. [Scotch® ATG Tapes]. (2000, August). Published raw data.

Anyoji, M., Numata, D., Nagai, H., & Asai, K. (2014). Pressure-sensitive paint technique for surface pressure measurements in a low-density wind tunnel (pp. 298-309, Tech.). The Author(s).

Bertoline, G., Wiebe, E., Hartman, N., & Ross, W. (2008). *Technical Graphics Communication* (4th ed.). Raleigh, NC: McGraw-Hill Education.

BMP388. (n.d.). Retrieved October 08, 2020, from https://www.bosch-sensortec.com/products/environmental-sensors/pressure-sensors/pressure-sensors-bmp388.html

Crouch, Jeffrey D. (2015, April). *European Patent EP 2937701 A1*. European patent offices.

Corson, B. W., Jr. (1943). The Belt Method for Measuring Pressure Distribution.

National Advisory Committee for Aeronautics, 1-8.

Freelin-Wade Co. (n.d.) *Multi-Colored Ribbon Tubing*. Retrieved from https://www.freelin-wade.com/polyurethane-ribbon-tubing-2M-013.html#1

Keith William (2002, October). US. Patent No US20040065146A1. United States. US patent office

Leitzke, J. P., & Zangl, H. (n.d.). *Feasibility of Wireless Pressure Sensors for Aircraft* (pp. 1-5, Tech. No. 9020). Klagenfurt: Alpen-Adria-Universit ̈at Klagenfurt Universitatsstraße.

McCarty, M. (2008). *The Measurement of the Pressure Distribution over the Wing of an Aircraft in Flight* (Master's thesis, University of New South Wales, 2008) (pp. 1-149). Newcastle: Australian Defence Force Academy.

MicroPressure Board Mount Pressure Sensors Compact, High Accuracy, Compensated/Amplified [Advertisement]. (2019). *MPR SERIES*, (F), 1-25.

Oreper, Boris, Brenneman John. (1999, February). US Patent No. US6272936B1. United States.

US Patent Office.

Pritchard, P. J. (2011). *Fox and McDonald's Introduction to Fluid Mechanics* (8th ed.). Hoboken, NJ: Wiley.

Rivers, N. A., VanDam, C. P., Brown, P. W., & Rivers, R. A. (2001). Flight Investigation of the Pressure-Belt Tubing Size Pressure Distributions. *NASA,* 1-46.

Rossow Vernon J. (1991, April). *US patent number 5233865A*. United states patent offices.

Stanton Joseph J. (1961, December). *US patent number 3214491.* United States patent offices.

Tanielian, M. H. (2001). *MEMS Multi-sensor System for Flight Testing* (Vol. 4599, pp. 120-129, Tech. No. 2499). Seattle, WA: SPIE.

Westphal, R. V., Drake, A., Bender, A., Bleazzard, M., Frame, D., & Jordan, S. R. (2006). *A Compact, Self-Contained System for Boundary Layer Measurements in Flight* (pp. 1-17, Tech. No. 3828). San Francisco, CA: American Institute of Aeronautics and Astronautics.

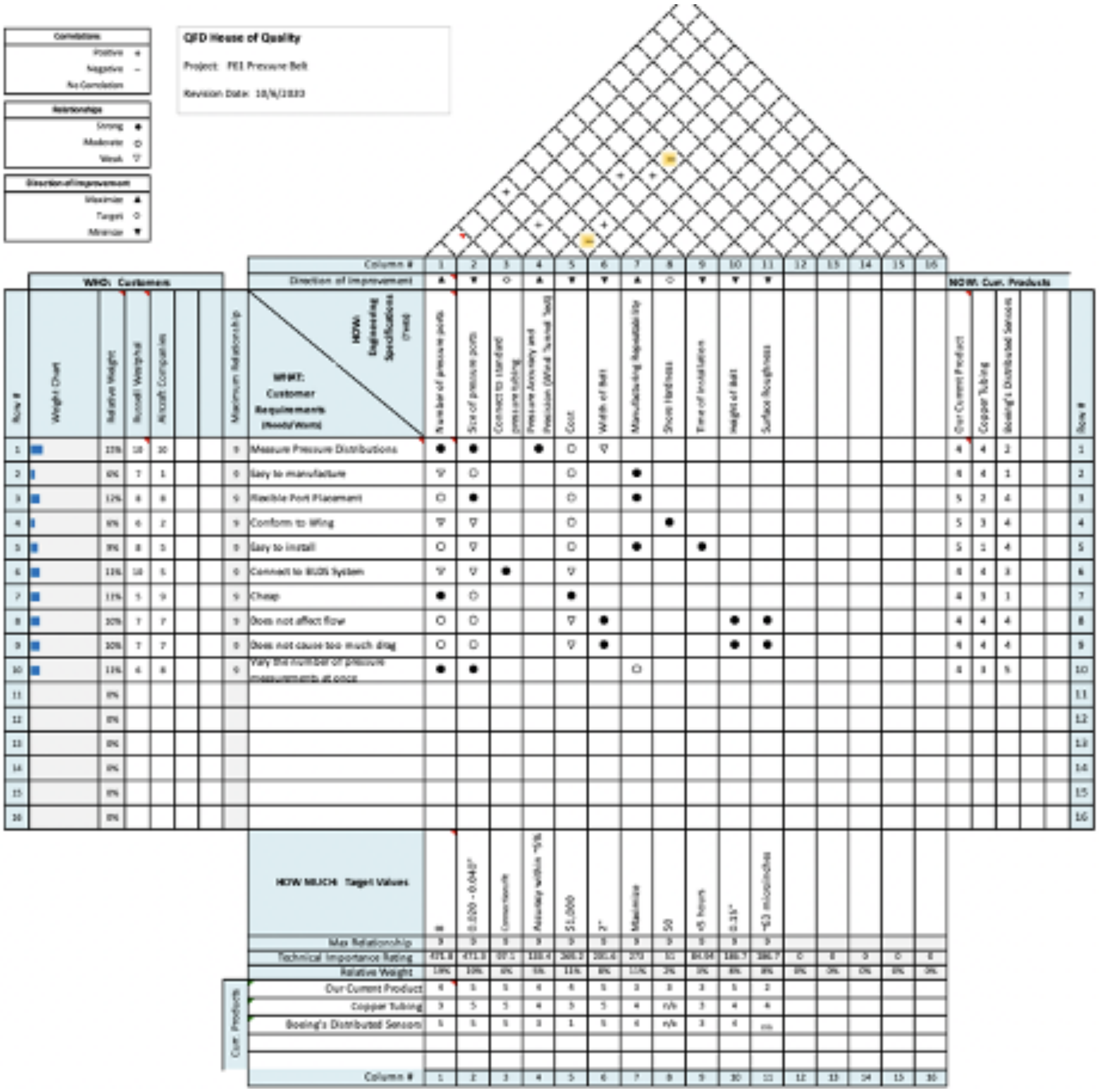
Westphal, R. V. (2020, August 26). *Pressure Belt Introduction & Specifications*. Lecture presented at Senior Project Introduction Presentation in CA, San Luis Obispo.

Zalovcik, J. A., & Wood, C. (1944). A FLIGHT INVESTIGATION OF THE EFFECT OF SURFACE ROUGHNESS ON WING PROFILE DRAG WITH TRANSITION FIXED. *National Advisory Committee for Aeronautics,* 1-16.

Zhou, Y., & Wang, Z. J. (2012). Effects of Surface Roughness on Separated and Transitional Flows over a Wing. *AIAA JOURNAL, 50*(No. 3), 593-609.

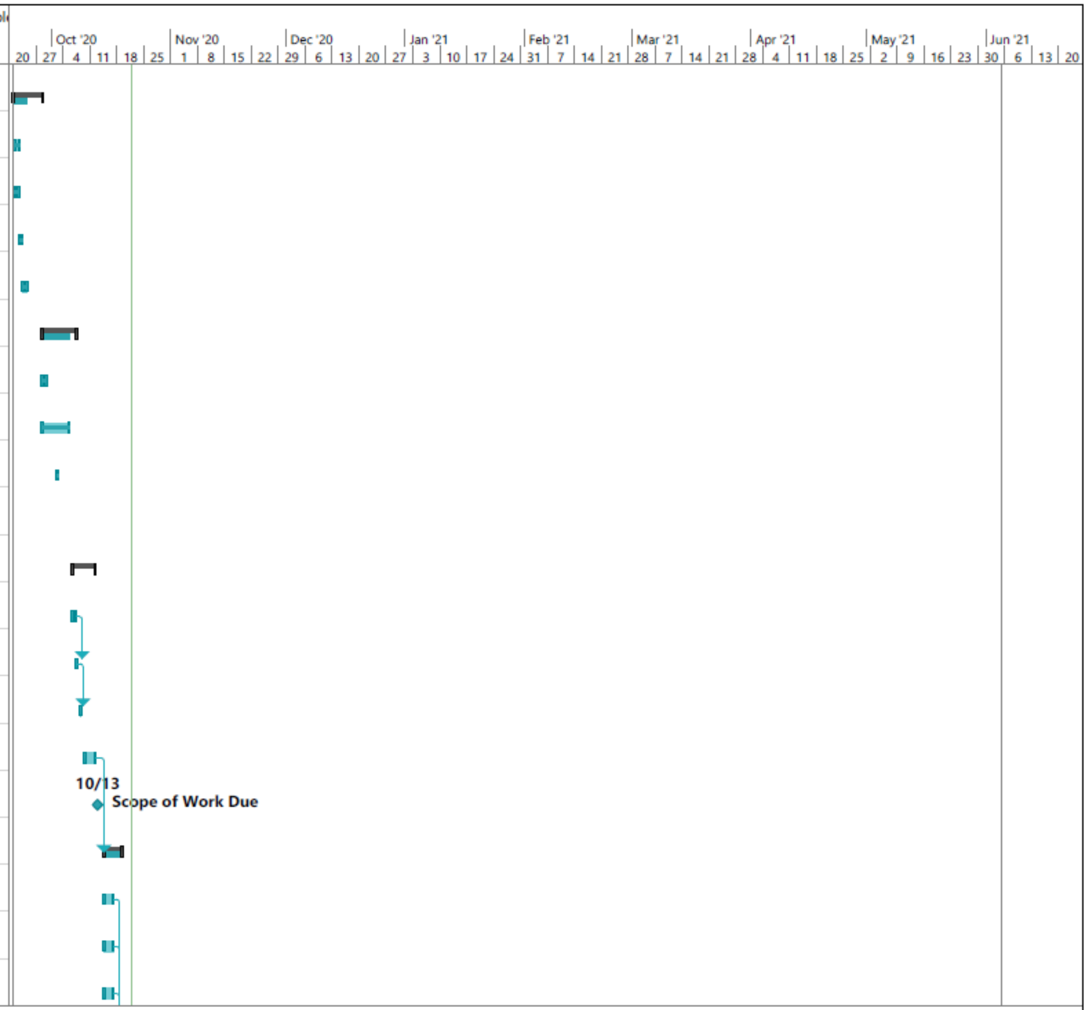
11.0 Appendices

Appendix A: QFD House of Quality

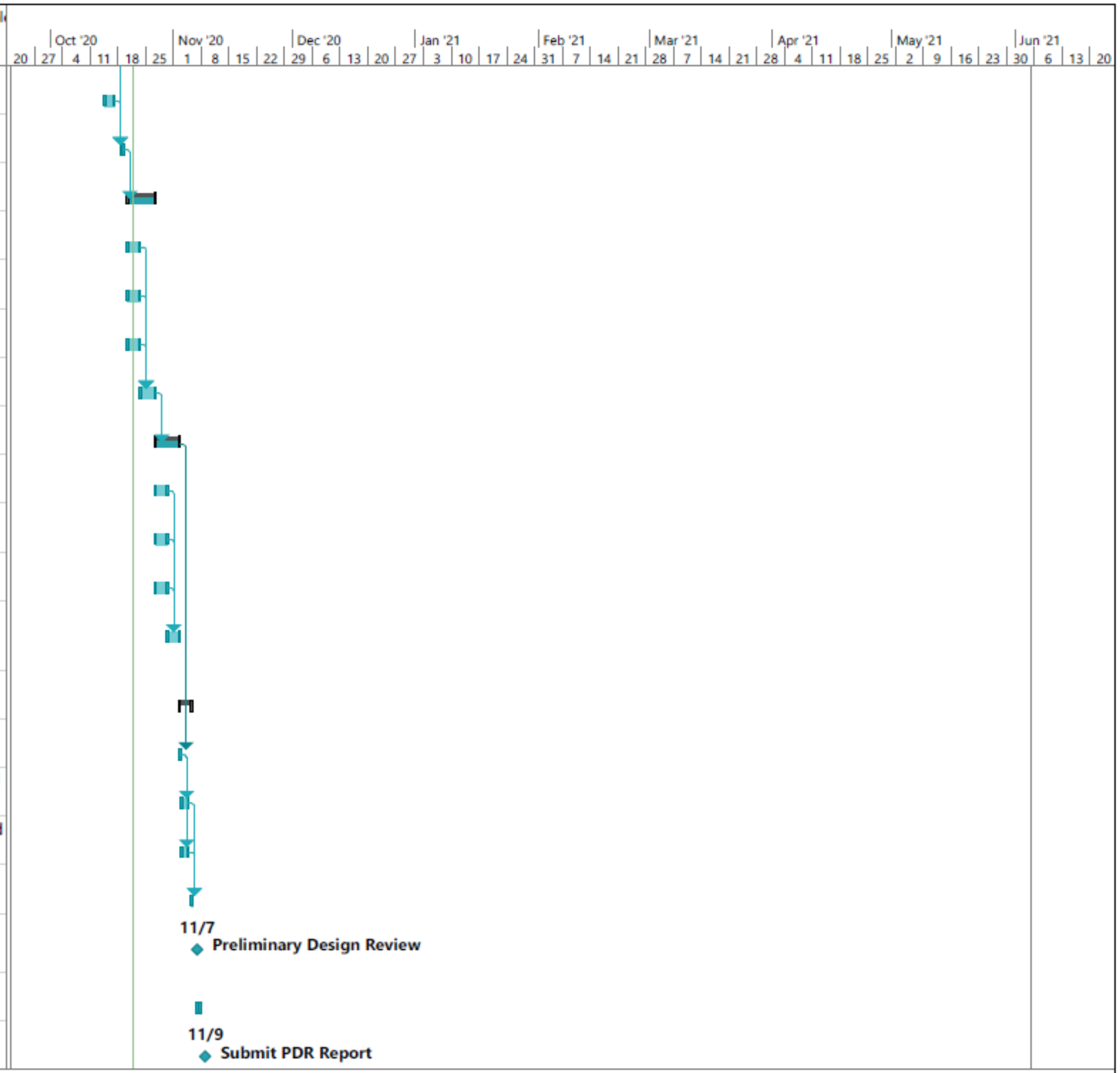


Appendix B: Gantt Chart

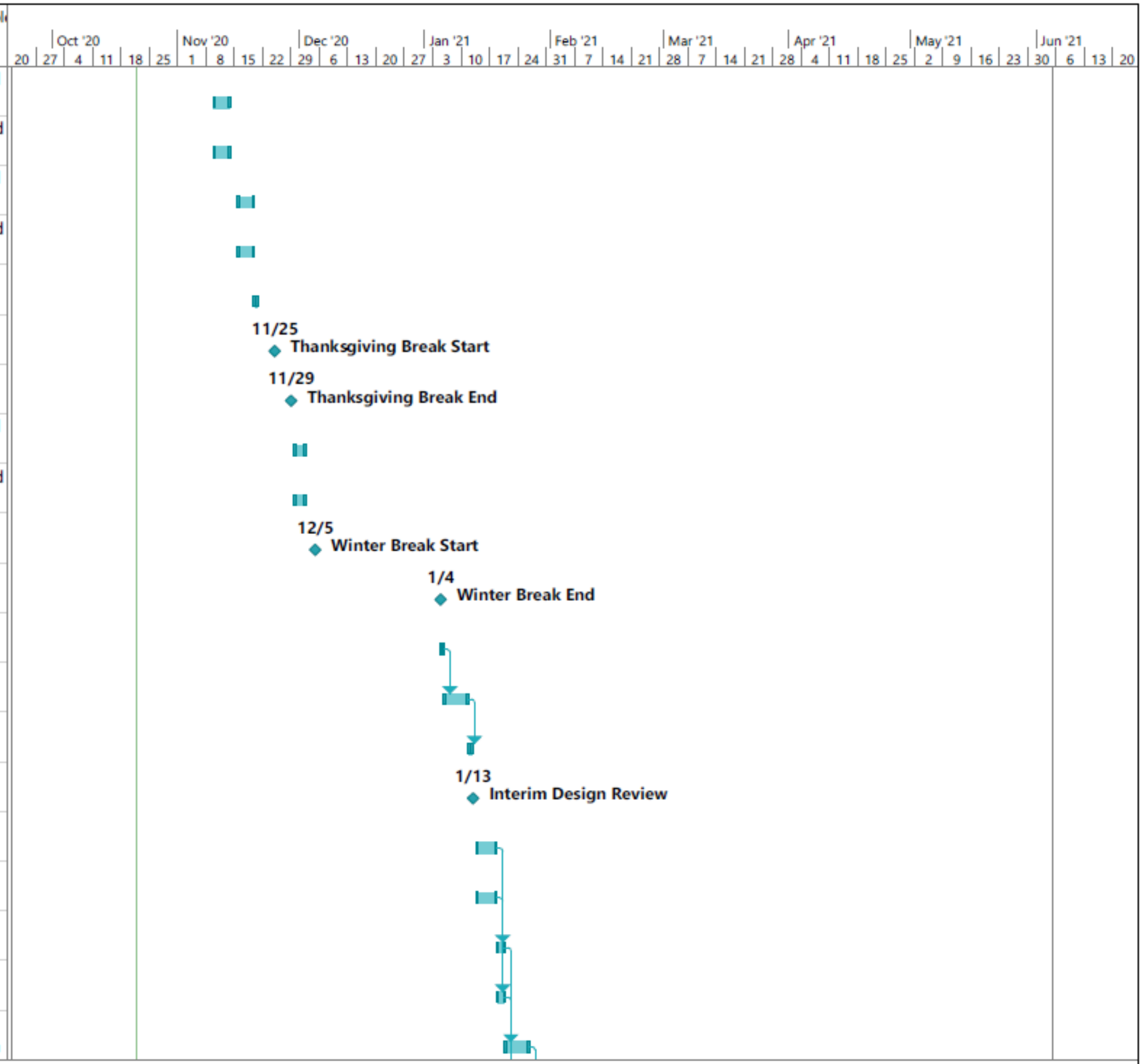
ID	Task Name	Responsible Team Member
3	**Perform Preliminary Research**	**4 of 4**
4	Conduct Patent Search	Sean
6	Search Library for Masters' Theses	Ben
5	Search for Previous Senior Projects	Biren
7	Search for Research Articles or Technical Documents	Hailey
8	**Research Potential Manufacturing Options**	**3 of 4**
11	Research Molding with Fiberglass	Biren
12	Research Pressure Sensors	Ben
9	Research Additive Manufacturing Belt	Sean
10	Research Molding with Silicone	Sean
13	**Analyze Manufacturing Viability**	**4 of 4**
15	Build House of Quality	Ben
14	Compile Design Matrix in OneNote	Hailey
17	Compare Design Matrix to HOQ	Hailey
16	Narrow Manufacturing Options to 3 Contenders	All
2	Scope of Work Due	All
28	**Create CAD Models of Manufacturing Options**	**All**
29	Model of Option 1	Sean
30	Model of Option 2	Hailey
31	Model of Option 3	Biren



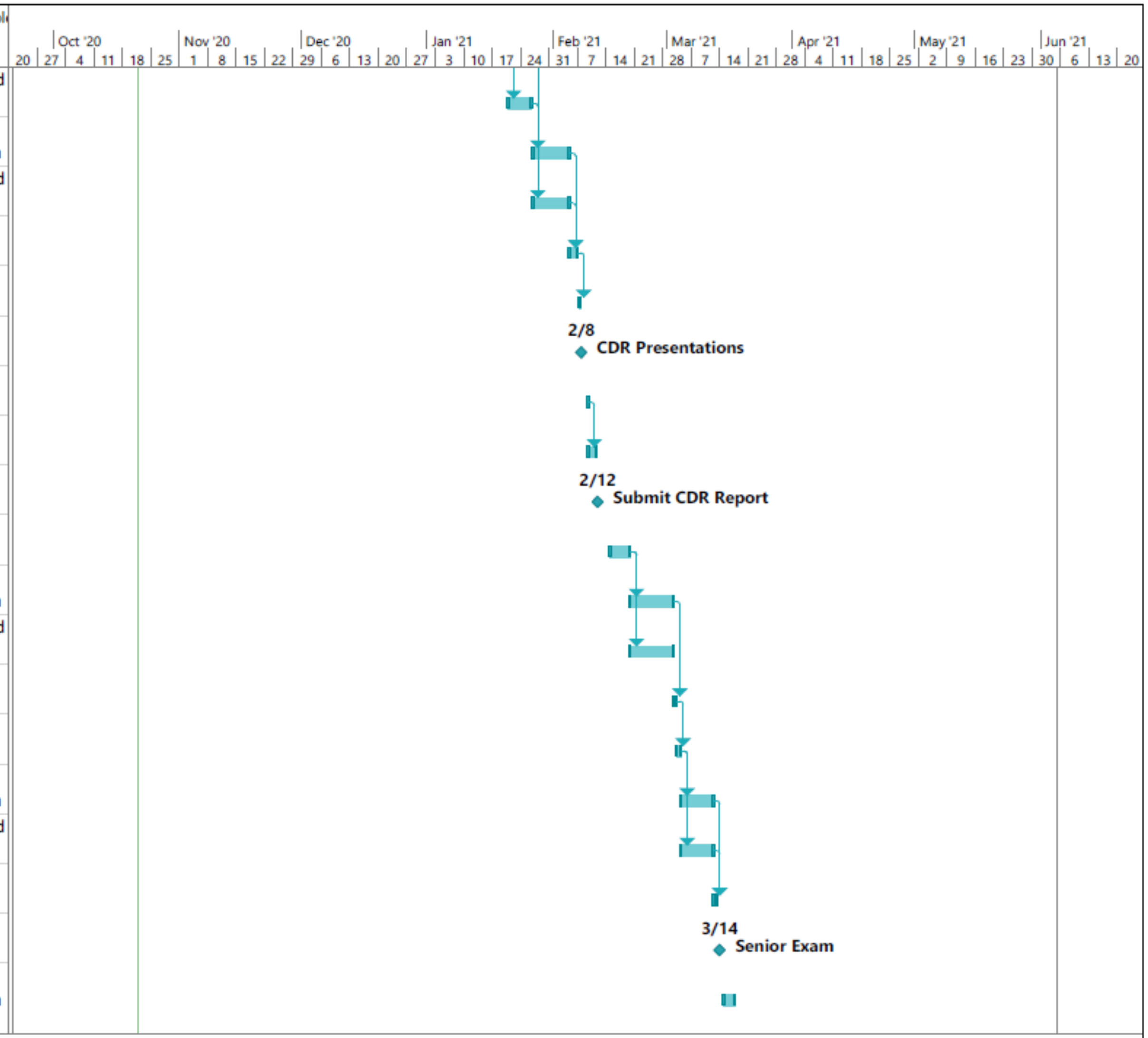
ID	Task Name	Responsible Team Member
33	Model of Option 4	Ben
32	Meet to Discuss Modeling Challenges	All
23	**Create Potential Materials List for Each Option**	**4 of 4**
24	Potential Materials List for Option 1	Sean
25	Potential Materials List for Option 2	Ben
26	Potential Materials List for Option 3	Hailey
27	Analyze How Many Options Can be Reasonably Pursued	All
18	**Perform Pricing Research and Budget Analysis**	**4 of 4**
19	Contact Vendor for Quote on Manufacturing Option 1	Sean
20	Contact Vendor for Quote on Manufacturing Option 2	Biren
21	Contact Vendor for Quote on Manufacturing Option 3	Hailey
22	Determine Pricing Feasabiltity in Relation to Budget and Possible Rework	Ben
34	**Prepare Presentation of Findings for PDR**	**4 of 4**
35	Whittle Down to 2 Options	All
36	Prepare Slides for Option 1	Sean and Hailey
37	Prepare Slides for Option 2	Biren and Ben
38	Meet to Practice Presentation	All
1	**Preliminary Design Review**	All
39	Review Preliminary Design Review Feedback	All
40	**Submit PDR Report**	All



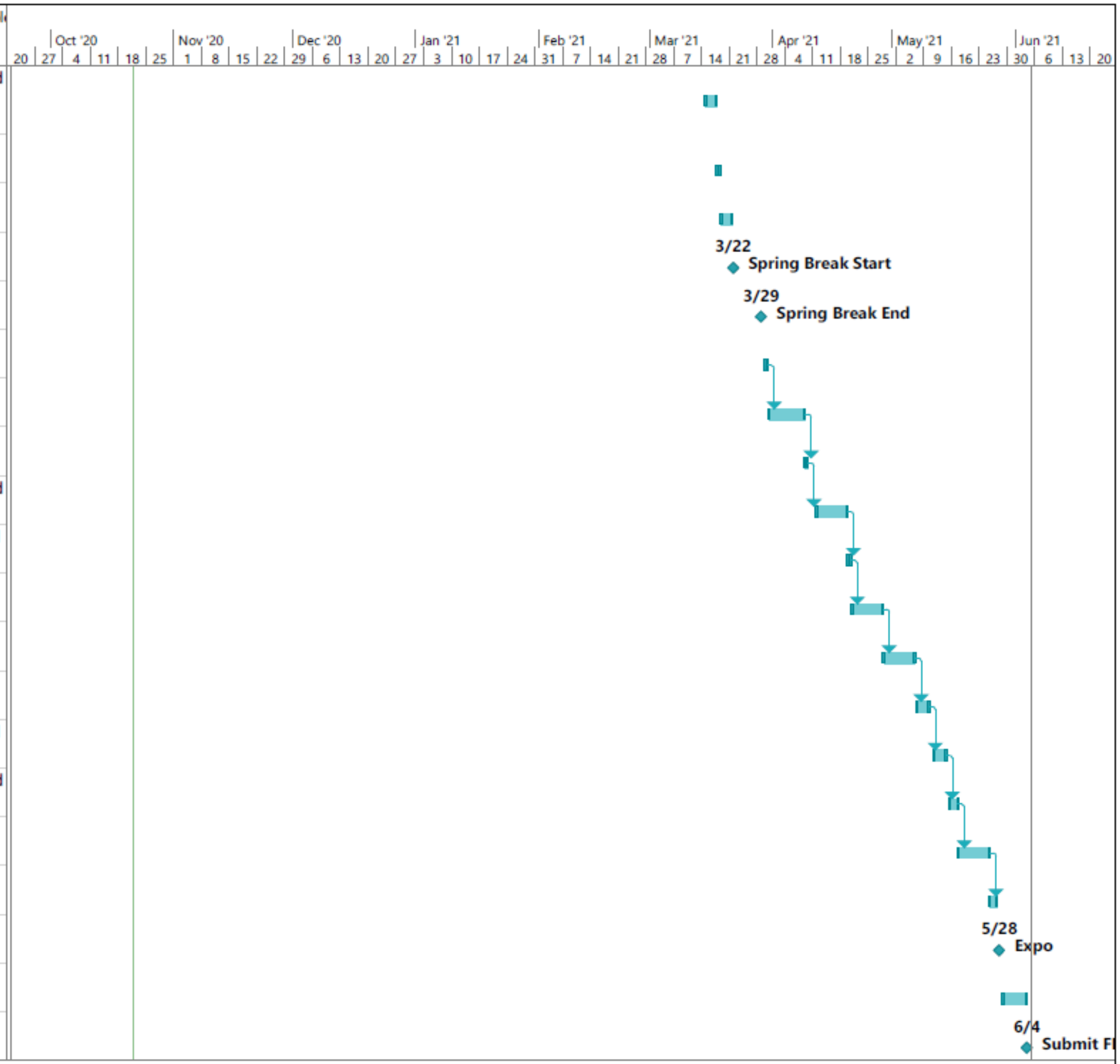
ID	Task Name	Responsible Team Member
41	Complete CAD Drawings for Option 1	Sean and Hailey
42	Complete CAD Drawings for Option 2	Biren and Ben
43	Create BOM for Option 1	Sean and Hailey
44	Create BOM for Option 2	Biren and Ben
45	Convene with Group for Full Material List	All
46	**Thanksgiving Break Start**	All
47	**Thanksgiving Break End**	All
48	Research Vendors for Option 1	Sean and Hailey
49	Research Vendors for Option 2	Biren and Ben
50	**Winter Break Start**	All
51	**Winter Break End**	All
52	Consolidate Vendor Data and Drawings	All
53	Organize Design Review Presentation	All
54	Practice Design Review Presentation	All
55	**Interim Design Review**	All
56	Contact Vendors for Quote on BOM 1	Hailey
57	Contact Vendors for Quote on BOM 2	Ben
58	Complete Forms for Purchase Orders for BOM 1	Sean
59	Complete Forms for Purchase Orders for BOM 2	Biren
62	Create Detailed Manufacturing Plan for Option 1	Hailey and Sean



ID	Task Name	Responsible Team Member
63	Create Detailed Manufacturing Plan for Option 2	Biren and Ben
79	Construct Prototype for Option 1	Hailey and Sean
80	Construct Prototype for Option 2	Biren and Ben
81	Create CDR Presentation	All
82	Practice CDR Presentation	All
64	**CDR Presentations**	All
65	Debrief and Review CDR Feedback	All
66	Compile CDR Report	All
67	**Submit CDR Report**	All
68	Develop Testing Protocol	All
69	Start CFD Analysis on Prototype 1	Hailey and Sean
70	Start CFD Analysis on Prototype 2	Biren and Ben
71	Schedule Testing for Project @ Fluids Lab	Ben
72	Run Simulations at Fluids Lab	All
73	Analyze Data Against Simulation 1 Results	Hailey and Sean
74	Analyze Data Against Simulation 2 Results	Biren and Ben
75	Prep for Senior Exam	All
76	**Senior Exam**	All
83	Prepare Pressure Field Visualization Data and Figures for Sim 1	Hailey and Sean



ID	Task Name	Responsible Team Member
84	Prepare Pressure Field Visualization Data and Figures for Sim 2	Biren and Ben
85	Meet to Discuss Conclusions and Rework	All
86	Compile Possible Changes and Successes	All
60	**Spring Break Start**	All
61	**Spring Break End**	All
87	Decide on Final Design Option	All
88	Reconstruct Final Prototype Mk2	All
89	Schedule Testing for Project @ Fluids Lab	Biren
90	Rerun Simulation for Final Prototype	Biren and Ben
91	Attend Testing at Fluids Lab	Sean and Hailey
92	Compile Data and Compare Results	All
93	Rework Project to Final Stage (Mk3)	All
94	Schedule Testing for Project @ Fluids Lab	Sean
95	Rerun Simulation for Final Prototype	Sean and Hailey
96	Attend Testing at Fluids Lab	Biren and Ben
97	Compile Data and Compare Results	All
98	Prepare Expo Poster and Results	All
77	**Expo**	All
99	Finalize Data and Figures (FDR)	All
78	**Submit FDR to Sponsor**	All



Appendix C: Pugh Matrices

Function: Does not interfere with floor

	Copper Tubes (DATUM)	Electronic Transducer	Resin Casting	3D print	Laser Cut	Gang of Tubes
Height		+	+	+	+	+
Roughness		-	+	+	+	S
Smooth attachment		+	+	+	+	+
Faired		-	+	+	+	S
Conform to wing		+	+	+	+	+
TOTALS		3	5	5	5	3

Function: Sponsor can manufacture

	Copper Tubes DATUM	Electronic Transducer	Resin Casting	3D print	Laser cut	Gang of tubes
Easy to manufacture	0	-	+	+	+	+
Cheap	0	-	S	-	-	S
Manufacture time	0	+	-	-	+	+
Accessibility to materials	0	-	-	+	-	S
TOTAL	0	-2	-1	0	0	2

Function: Attach to wing

	1	2	3	4	5	6
Conform To Wing	DATUM	+	+	+	+	+
Easy to Install	DATUM	+	+	+	+	+
Does not cause too much drag	DATUM	S	-	+	+	+
Does not affect flow	DATUM	S	-	+	+	S
Totals:	0	2	0	4	4	3

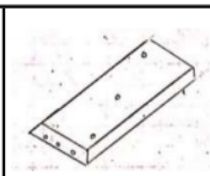
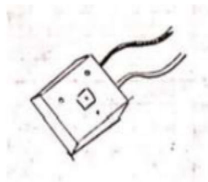
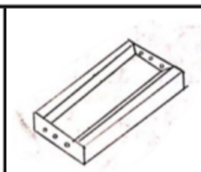
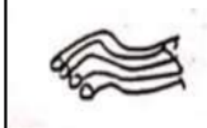
1. Copper Sweated Tubes
2. Plastic gang of tubes
3. Laser cut vias
4. 3D Printed Beld
5. Casting Belt
6. Distributed Sensors

Function: Interface with BLDS						
	Sweated Copper Tubing	Electronic Transducer	Resin Casting	3D Printing	Laser Cutting	Gang of Tubes
Does Not Affect Flow	DATUM	-	+	+	-	-
Easy to Install		+	+	+	+	+
Simple to Connect		+	-	-	-	+
Rougness		-	+	+	+	-
Conforms to Wing		+	+	-	-	-
TOTAL		3	4	3	2	2

C-3

Weighted Decision Matrix

Team F61: Pressure Belt

		 3D printing		 Electric Transducer		 Resin Casting		 Gang of Tubes	
Specification	Weight	Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted
Number of pressure ports	19	10	190	10	190	10	190	7	133
Size of pressure ports	19	7	133	10	190	7	133	7	133
Connect to standard pressure tubing	5	6	30	3	15	6	30	7	35
Pressure Accuracy and Precision	6	7	42	9	54	7	42	7	42
Cost	11	5	55	4	44	7	77	6	66
Width of belt	8	7	56	8	64	7	56	5	40
Manufacturing Repeatability	11	6	66	8	88	6	66	9	99
Shore Hardness	2	10	20	10	20	10	20	10	20
Time of installation	3	7	21	9	27	7	21	2	6
Height of belt	8	8	64	10	80	8	64	7	56
Surface roughness	8	9	72	8	64	8	64	2	16
Totals:	**100**		**749**		**836**		**763**		**646**

Appendix D: Ideas Generated during Ideation

First Session

- Pressure sensitive paints – there are certain paints that change luminance depending on the pressure applied on it.
- Distributed Sensors – Use electronic sensors distributed across the wing to measure pressure.
- Laser cut a pressure belt – use a laser cutter to cut the vias through which pressure would be conducted.
- 3D Printed Belt – Use 3D printing to print a flexible belt which has the complex internal features for a pressure belt.
  - This could be done with SLA, PolyJet, or FormLabs printing.
- Use the previous method of the gang of plastic tubes.
- Use rigid copper tubing.
- 3D print a mold and cast the belt using silicone – use wires to create the channels within
- Mount pressure diaphragm to the wing – route data to BLDS electrically

Worst Idea Ideation

- Use plastic straws – The bore size is too large, and it is not aerodynamic, likely flimsy.
- Hot glue casting – The material is not good for casting and it would be hard to release any cores.
- Drill holes into the wing – The method must not be destructive.
- Use the weather airspeed cups – This method would affect the airflow.
- Cast out of clay – too rigid.

Appendix E: CDR Hand Calculations

Independent Variables	
Height (in)	Q (psi)
0.080	0.694
0.090	1.389
0.100	2.083
0.110	2.778
0.120	
0.130	
0.140	
0.150	

Constants							
Misalignment Angle (°)	C_d	L_{belt} (in)	$\tau_{Adhesive}$ (psi)	$w_{Belt,bottom}$ (in)	$w_{Belt,top}$ (in)	Silicone Density (lbm/ft^3)	Weight perHeight (lbf/in)
15	0.5	36	2	0.740	0.5	67.5	0.873

This spreadsheet calculates the frictional forces on the belt adhesive at a misalignment angle of 15 degrees at a variety of different dynamic pressures. The weight is also added in as pulling straight down, contributing fully to shear along the primary shear direction. Therefore both drag and weight are imparting a shear force on the adhesive in the highest possible loading case. This analysis computes the shear forces by using the chord and span components of the dynamic pressure, which is a conservative approach. Even with all worst case scenarios used in the analysis, we have a factor of safety of 26 at the worst shape and loading possible.

Calculations with Weight and Solid Trapezoid (Fuselage Install)																
Const.	100 psf				200 psf				300 psf				400 psf			
Height (in)	$F_{Side\ Load}$ (lbf)	$F_{Front\ Load}$ (lbf)	τ_{Belt} (psi)	FOS	$F_{Side\ Load}$ (lbf)	$F_{Front\ Load}$ (lbf)	τ_{Belt} (psi)	FOS	$F_{Side\ Load}$ (lbf)	$F_{Front\ Load}$ (lbf)	τ_{Belt} (psi)	FOS	$F_{Side\ Load}$ (lbf)	$F_{Front\ Load}$ (lbf)	τ_{Belt} (psi)	FOS
0.080	0.329	0.017	0.012	161.923	0.587	0.033	0.022	90.553	0.846	0.050	0.032	62.850	1.105	0.067	0.042	48.126
0.090	0.370	0.019	0.014	143.931	0.661	0.037	0.025	80.491	0.952	0.056	0.036	55.867	1.243	0.075	0.047	42.779
0.100	0.411	0.021	0.015	129.538	0.734	0.042	0.028	72.442	1.058	0.062	0.040	50.280	1.381	0.083	0.052	38.501
0.110	0.452	0.023	0.017	117.762	0.808	0.046	0.030	65.857	1.164	0.069	0.044	45.709	1.519	0.091	0.057	35.001
0.120	0.493	0.025	0.019	107.948	0.881	0.050	0.033	60.369	1.269	0.075	0.048	41.900	1.658	0.100	0.062	32.084
0.130	0.534	0.027	0.020	99.645	0.955	0.054	0.036	55.725	1.375	0.081	0.052	38.677	1.796	0.108	0.068	29.616
0.140	0.575	0.029	0.022	92.527	1.028	0.058	0.039	51.744	1.481	0.087	0.056	35.914	1.934	0.116	0.073	27.501
0.150	0.616	0.031	0.023	86.359	1.101	0.062	0.041	48.295	1.587	0.094	0.060	33.520	2.072	0.125	0.078	25.667

The governing equations are:

$$F_{drag} = C_d Q A \cos\beta$$

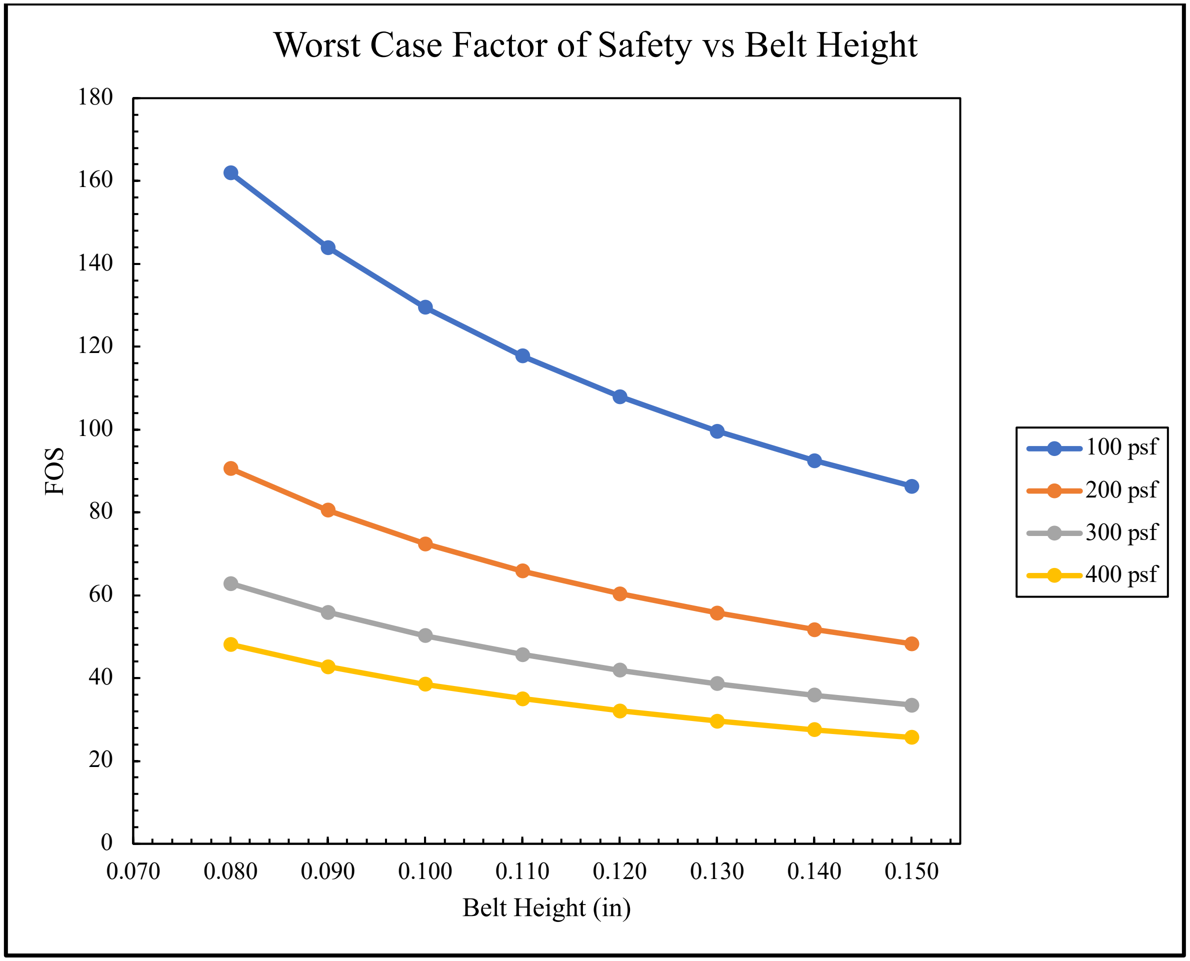
Where C_d is the drag coefficient, Q is the dynamic pressure, A is the side area of the belt, and β is the skew angle between the belt and the free stream.

Then the factor of safety is given by:

$$FOS = \frac{\tau_{max} w l}{F_{drag}}$$

Where τ_{max} is the max adhesive lap strength of the transfer adhesive, and w and l are the width and length of the belt respectively.

E-2



Worst Case Factor of Safety vs Belt Height
FOS
180
160
140
120
100
80
60
40
20
0
0.070
0.080
0.090
0.100
0.110
0.120
0.130
0.140
0.150
Belt Height (in)
100 psf
200 psf
300 psf
400 psf

Appendix F: Design Hazard Checklist

PDR Design Hazard Checklist **Project F61 Pressure Belt**

Y	N	
	●	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	●	2. Can any part of the design undergo high accelerations/decelerations?
	●	3. Will the system have any large moving masses or large forces?
	●	4. Will the system produce a projectile?
	●	5. Would it be possible for the system to fall under gravity creating injury?
	●	6. Will a user be exposed to overhanging weights as part of the design?
●		7. Will the system have any sharp edges?
	●	8. Will any part of the electrical systems not be grounded?
	●	9. Will there be any large batteries or electrical voltage in the system above 40 V?
	●	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	●	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	●	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
●		13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	●	14. Can the system generate high levels of noise?
●		15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
	●	16. Is it possible for the system to be used in an unsafe manner?
●		17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, on the reverse side add:
(1) a complete description of the hazard,
(2) the corrective action(s) you plan to take to protect the user, and
(3) a date by which the planned actions will be completed.

PDR Design Hazard Checklist **Project F61 Pressure Belt**

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
The system will have sharp points on the ends of the wires used as negatives for the cast.	Use gloves to handle wires when preparing the mold for casting		
Certain casting materials may have health hazards associated with their use.	Follow instructions on Safety Data Sheet for the material.		
The device will be mounted on an aircraft wing during flight tests.	Choose a material that can survive those conditions.		
A vacuum chamber will be used to remove air bubbles during casting.	Follow safety guidelines for casting.		

Appendix G: Purchasing List

Material	Vendor	iBOM Part Number	Vendor Part Number	Purchaser	Purchasing Website	Cost Per Unit	Quantity	Total Cost
PLA 3D Printer Filament, 1kg spool, 1.75 mm, White	HATCHBOX	110000	-	Sponsor	amazon.com	$ 15.14	1	$ 15.14
0.042" 304 Stainless Steel Tubing, 3ft	McMaster-Carr	111000	8988K52	Sponsor	mcmaster.com	$ 15.14	8	$ 121.12
Epoxy Glue	McMaster-Carr	111100	1813A351	Sponsor	mcmaster.com	$ 17.58	1	$ 17.58
SORTA-Clear 40 Trial Unit	Reynold's Advanced Materials	111210	-	Sponsor	reynoldsam.com	$ 40.87	1	$ 40.87

Appendix H: Drawing Package

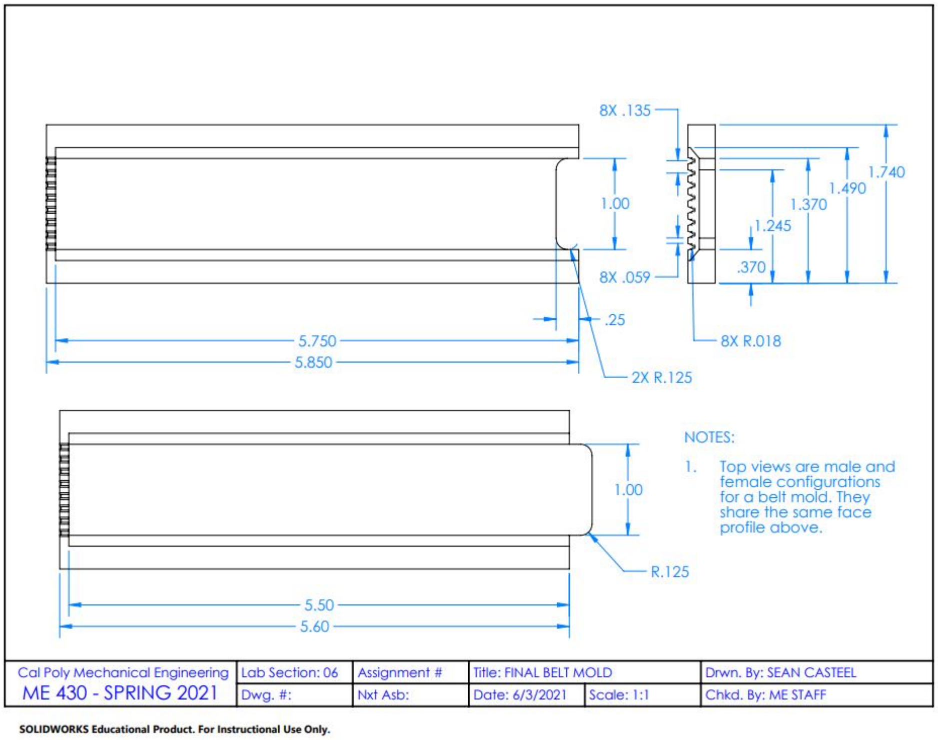


Figure H.1 Left Pressure Belt mold in 0.063" via a 5-hole configuration

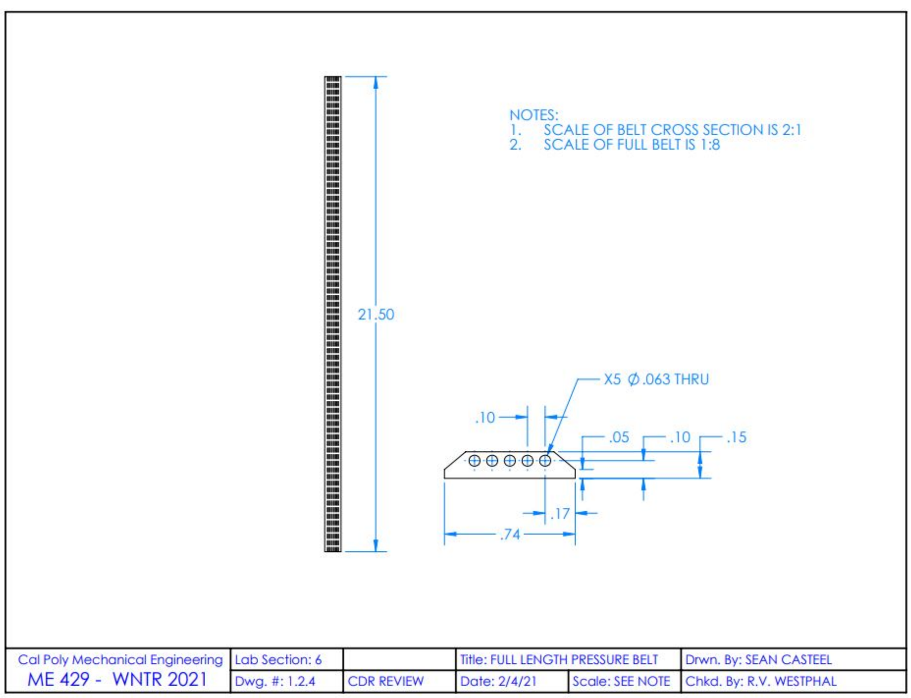


Figure H.2 Pressure Belt Mold 0.063” via and 5-hole configuration

Appendix I: iBOM

Pressure Belt

Indented Bill of Material (iBOM)

Assembly Level	Part Number	Description	Qty	Cost	Ttl Cost	Source	More Info
		Lvl0 Lvl1 Lvl2 Lvl3 Lvl4					
0	100000	Final Assy				------	
1	110000	Mold	1	29.63	29.63	Amazon HATCHBOX PLA	3D print
2	111000	Core inserts	5	15.14	75.7	McMaster	Stainless steel, Part #8988K52
2	111100	Epoxy/glue	1	17.58	17.58	McMaster	Part # 1813A351
2	111200	Belt	-		-	custom	
3	111210	Silicone	1	40.87	60.87	SORTA-Clear 40 Trial Unit	
3	111230	Biopsy punch	1			McMaster	Prof. Westphal has these
1	120000	0.040 in Couplings	1			McMaster	Prof. Westphal already has these
	Total Parts		9				

Appendix J: Purchase Critical Specifications

3D Printer Filament

- PLA Filament
- 1.75 mm diameter filament

0.042” Steel Tubing

- Tube diameter must be around 0.040”, up to a maximum 0.063”
- Tube must be straight, around 3 ft long
- Tube must have a smooth metal surface

Epoxy

- Must be able to attach plastics and be sanded
- Strong attachment is not a huge concern
- Quick hardening time is important

Silicone

- Shore Hardness of 40A
- Clear
- 60 min pot life

Appendix K: Design Failure Mode and Effects Analysis

Design Failure Mode and Effects Analysis

Product: Pressure Belt

Team: F61

Prepared by:
Sean Casteel, Biren Rama, Hailey Earnest, Benjamin Bons

Date: November 19, 2020 (orig)

													Action Results			
System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Severity	Occurence	Criticality
Mold / provide shape for casting	mold does not print properly	resulting cast will not be the correct shape, causing drag	7	1) error in 3D printer 2) error in original CAD model	1) Configure 3D Print slicer for tightest tolerance	5	1) Measure critical dimensions after print	2	70	Review current CAD model to check for any geometry that could cause issues with the print	Biren, 12/7	CAD was reviewed	7	5	35
Mold / support wire core inserts	mold does not print properly, wire inserts are not aligned	vias may be crooked or collapse leading to inaccurate measurements	7	1) error in 3D printer 2) error in original CAD model	1) Ensure printer resolution is sufficient for hole size	2	1) level check 2) visual inspection during cast	1	14	Review current CAD model to check for any geometry that could cause issues with the print	Hailey 12/7	CAD was reviewed	7	2	14
Mold/allow for easy casting	Cast sticks to 3D printed mold and doesn't release	Belt body may tear or otherwise not be in the desired shape, causing drag or bad adherence	7	1) Not enough release agent 2) environmental effects that cause pieces to stick	1) Apply mold release 2) Sand and smooth Mold 3) Design draft angle	4	1) Visual Inspection 2) Leak and Flow Test	2	56	1) Add a tab to release mold quickly	Sean 12/12	Mold was tested and no issues occured with removing casted silicone from the mold	7	4	28
Mold / allow for easy casting	Wire inserts get stuck inside the cast belt	Pressure vias could tear, leading to leaks or other loss of integriy, causing bad data	8	1) material properties do mesh well and become bonded 2) wire kinks during casting process	1) Use smooth wire inserts 2) Use mold release 3) Ensure no kinks in the wire	4	1) Visual Inspection 2) Leak and Flow Test	2	64	Test different types of wire	Sean 12/12	Different types of wire were tested. Hypo tubing was the most successful and did not get stuck in the mold	8	4	32
Mold / allow for easy casting	Cast is impure or has bridges or air pockets	Data is inaccurate	8	1) Improper outgassing 2) wires touch the surface of the mold	1) use heat gun to remove air bubbles 2) pull vacuum on cast and medium	6	1) Use clear silicone for a visual inspection 2) Use bright light to see the light spots in a belt.	3	144	Test different methods for getting rid of impurities	Sean 12/12	Heat gun was applied. Next set of testing is to try slower stirring or apply an outgassing system	8	6	48
Mold / allow for easy casting	Wires snap/Mold can't withstand tension	Cast failure, potential harm to user, bad mold shape	8	1) Overtension of wire 2) Bearing failure at core holes	1) Determine min tension needed on wire 2) Get high strength wires	4	1) Use a tuner to determine the harmonic of the wire to ensure we don't overtension	6	192	Use rigid cores that don't require tension	Biren, 12/14	Hypo tubing was tested and does not require tensioning	8	1	8
Cast belt / measure pressure	pressures made unstable by cast finish	data is bad	8	1) inserts too rough 2) cores not aligned 3) rod straightness off	1) deflection analysis 2) fastener shear analysis	4	1) surface finish roughness check	2	64	Perform preliminary analysis in different inserts	Biren, 2/10	Testing still in progress	8	4	32
Cast belt / interface with BLDS	cast belt does not have appropriate ID for interfacing	data is bad due to leak	8	1) leak occurs due to size 2) probe cant seat in via 3) pressure drop halfway through belt	1) probe check	6	1) leak check with hand pump	2	96	Determine how to include couplings in the cast	Ben, 1/24	Size of couplings is still being determined	8	6	48
Cast belt / does not greatly interfere with flow	cast belt is too tall in profile	data is bad due to high profile	6	poor design (i.e. does not fit dimensional criteria)	1) calculation with flow impact 2) slender body theory FoS check	3	1) Wind tunnel testing 2) comparison to known data	3	54	Perform preliminary analysis on belt size effects on wind flow	Hailey, 2/10	Leak and flow test will be performed	6	3	18
Cast belt / attach to aircraft	cast belt falls off after adhering	entire system failure	8	1) adhesive not applied properly 2) adhesive not strong enough to withstand load	1) adhesion analysis with 15 deg off freestream & slender body theory	2	1) stick test w/ compressed air	4	64	Research/ test multiple kinds of adhesive	Ben 1/24	Dr. Westphal has a recommended adhesive to use	8	2	16

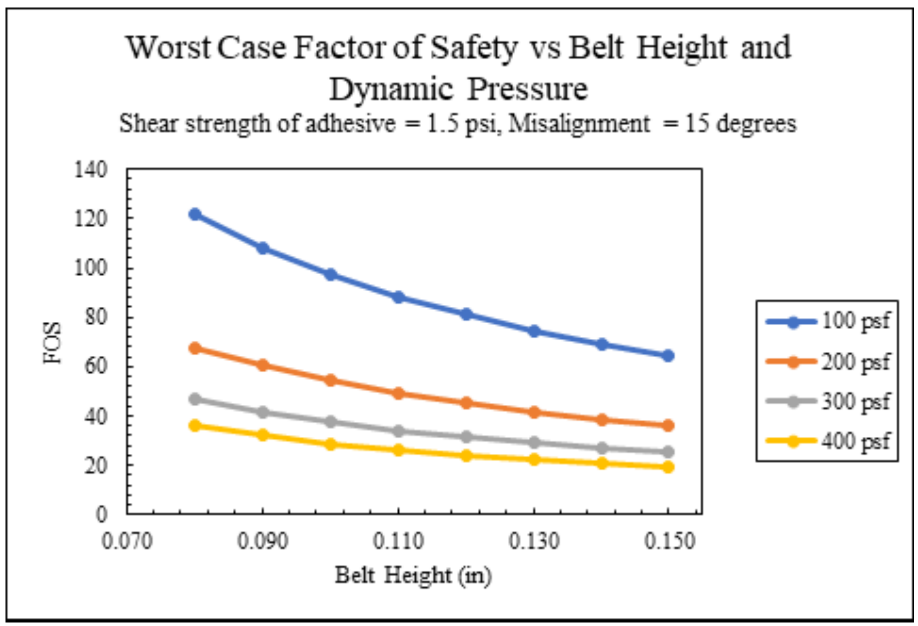
Appendix L: Design Verification Plan

DVP&R - Design Verification Plan (& Report)											
Project:	F61 Pressure Belt		Sponsor:	Dr. Westphal					Edit Date:	5/31/2021	
TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING		Numerical Results	Notes on Testing
								Start date	Finish date		
1	Leak Test	Pressurize and seal individual channels of the belt, and see if the channel can hold pressure over time. Compare the leak rate with the leak rate of a known leak-free tube	Time to lose the pressure	Pass/Fail if leak rate is within 5% of the known tube	Hand pump	Air, silicone belt	Sean	2/15/2021	4/15/2021	8/8 vias pass	Belt vias should not leak.
2	Flow Test	Run air through each individual via and check that air flow held constant.	Air flow rate	Pass/Fail if obstruction occurs	Hand pump	Silicone belt	Sean	3/20/2021	4/16/2021	8/8 vias pass	Belt vias had no obstructions to block flow.
3	Voids	Visual insection of clear belt to look for bridging between 2 vias, or surface roughness	None	Pass/Fail	None	Silicone Belt	Sean	2/18/2021	4/17/2021	8/8 vias pass	No large voids were present in the manufacturing process or finished part.
4	Adhesive Test	Determine the shear force required to remove belt with adhesive from wing model	Width and length of adhesive, cure time, force at yield, shear stress at yield	Pass Criteria: Yield occurs after 2psi	Spring scale, silicone belt, airfoil surface/wing model, vise to hold wing model	Silicone belt, adhesive, tubing couplers	Biren	5/10/2021	5/11/2021	See AdhesiveShearStrengthTest.xslx	Adhesive should not be an issue for expected loads on the belt. Peel strength is extremely low as expected, but this load case is unlikely.
5	Wind Tunnel Test	Determine if the pressure belt can used to accuractely take pressure measurements on an airfoil	Pressure measurements at designated locations	Pass Criteria: Accuracy within 1% of known data	Airfoil, wind tunnel	Silicone belt, adhesive, tubing couplers	Ben	5/19/2021	5/28/2020	See WindTunnelData.xslx	Leading edge has worst correlation. Some problems near port 5, right around belt seam.

From AdhesiveShearStrengthTest.xslx

	Peak Force		Uncertainty	Shear Force		Uncertainty F	Uncertainty L	Uncertainty W	TOTAL UNCERTAINTY
Run 1	4.74	lbf	0.005	2.37	psi	-0.0025	0.071818182	0.036461538	0.080582535
Run 2	3.14	lbf	0.005	1.57	psi	-0.0025	0.047575758	0.024153846	0.05341452
Run 3	5.78	lbf	0.005	2.89	psi	-0.0025	0.087575758	0.044461538	0.098247604
NEW TRANSFER ADHESIVE									
Run 4	6.2	lbf	0.005	3.1	psi	-0.0025	0.093939394	0.047692308	0.105382237
Run 5	4.98	lbf	0.005	2.49	psi	-0.0025	0.075454545	0.038307692	0.084658831
POINT LOAD									
Run 6	2.96	lbf	0.005	1.48	psi	-0.0025	0.044848485	0.022769231	0.050359453

GOOD RUNS HIGHLIGHTED IN GREEN



Appendix M: Project Budget

Purchase List

Material	Vendor	iBOM Part Number	Vendor Part Number	Purchaser	Purchasing Website	Unit Cost	Quantity	Total Cost	Purchased?	Purchase Date
PLA 3D Printer Filament, 1kg spool, 1.75 mm, White	HATCHBOX	110000	-	Sponsor	amazon.com	$ 15.14	1	$ 15.14	Y	01/11/2021
0.042" 304 Stainless Steel Tubing, 3ft	McMaster-Carr	111000	8988K52	Sponsor	mcmaster.com	$ 15.14	1	$ 15.14	Y	01/11/2021
SORTA-Clear 40 Trial Unit	Reynold's Advanced Materials	111210	-	Sponsor	reynoldsam.com	$ 40.87	1	$ 40.87	Y	01/11/2021
Magnet Wire, 200C, 18 AWG - 2oz / 25'	Remington Industires	N/A	18H200P.125	Sponsor	remingtonindustries.com	$ 7.11	1	$ 7.11	Y	01/11/2021
Undersized 0.040" Steel Tubing	McMaster-Carr	N/A	3009A276	Sponsor	mcmaster.com	$ 2.38	5	$ 11.90	Y	01/11/2021
Nitride-Coated H13 Tool Steel Ejector Pin - 6", 3/64" dia	McMaster-Carr	111000	93772A104	Sponsor	mcmaster.com	$ 5.48	5	$ 27.40	Y	01/11/2021
Hardened Undersized High-Speed M2 Tool Steel Rod	McMaster-Carr	N/A	3009A289	Sponsor	mcmaster.com	$2.29	1	$ 2.29	Y	02/16/2021
Hardened Undersized High-Speed M2 Tool Steel Rod	McMaster-Carr	N/A	3009A288	Sponsor	mcmaster.com	$2.29	1	$ 2.29	Y	02/16/2021
304 Stainless Steel Tubing	McMaster-Carr	111000	8987K54	Sponsor	mcmaster.com	$18.06	1	$ 18.06	Y	02/16/2021
304 Stainless Steel Tubing	McMaster-Carr	111000	8988K52	Sponsor	mcmaster.com	$15.14	2	$ 30.28	Y	02/16/2021
304 Stainless Steel Tubing	McMaster-Carr	111000	8987K54	Sponsor	mcmaster.com	$18.06	5	$ 90.30	Y	02/25/2021
304 Stainless Steel Tubing	McMaster-Carr	111000	8987K54	Sponsor	mcmaster.com	$18.06	5	$ 90.30	Y	04/15/2021
304 Stainless Steel Tubing	McMaster-Carr	111000	8987K54	Sponsor	mcmaster.com	$18.06	4	$ 72.24	Y	05/05/2021

Budget	Total Spent	Total Remaining
$ 1,000.00	$ 423.32	$ 576.68

Appendix N: Risk Assessment

designsafe Report

Application:	PressureBelt	Analyst Name(s):	
Description:	A belt to measure pressures	Company:	
Product Identifier:		Facility Location:	
Assessment Type:	Detailed		
Limits:			
Sources:			
Risk Scoring System:	ANSI B11.0 (TR3) Two Factor		

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-1	Sponsor (Russ) Apply transfer adhesive	chemical : reaction to / with irritant chemicals Transfer adhesive might be an irritant	Minor Likely	Low	gloves	Minor Remote	Negligible	On-going [Daily] Biren
1-1-2	Sponsor (Russ) Apply transfer adhesive	chemical : skin exposed to toxic chemical Transfer adhesive might be an irritant	Moderate Unlikely	Low	Gloves	Minor Remote	Negligible	On-going [Daily] Sean
1-2-1	Sponsor (Russ) Insert plumbing	mechanical : cutting / severing Metal inserts can puncture your skin.	Minor Remote	Negligible	Train user	Minor Remote	Negligible	On-going [Daily] Ben
1-3-1	Sponsor (Russ) Pressure cure apparatus	mechanical : crushing Pressure apparatus has a armature that clamps and can pinch or crush the user	Serious Unlikely	Medium	Train user	Serious Unlikely	Medium	On-going [Daily] Hailey
1-3-2	Sponsor (Russ) Pressure cure apparatus	mechanical : pinch point Pressure apparatus has a armature that clamps and can pinch or crush the user	Serious Unlikely	Medium	Train user	Serious Unlikely	Medium	On-going [Daily] Biren
2-1-1	Manufacturer/Research assistant Print mold	electrical / electronic : improper wiring If 3D printer is not wired correctly, electrical problems might occur	Serious Remote	Low	Test for proper wiring. Use reliable printer	Serious Remote	Low	On-going [Daily] Sean
2-1-2	Manufacturer/Research assistant Print mold	heat / temperature : burns / scalds Extruding nozzle gets hot	Moderate Remote	Negligible	"Don't touch the nozzle" warning sticker	Moderate Remote	Negligible	On-going [Daily] Ben

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-1-3	Manufacturer/Research assistant Print mold	ventilation / confined space : smoke Improper set up can cause overheating and burning of filiment	Minor Unlikely	Negligible	Ventilate	Minor Remote	Negligible	On-going [Daily] Hailey
2-2-1	Manufacturer/Research assistant Glue together mold segments	chemical : reaction to / with irritant chemicals Glues can be hazardous	Minor Unlikely	Negligible	Gloves, buy non-hazardous glues	Minor Remote	Negligible	On-going [Daily] Biren
2-2-2	Manufacturer/Research assistant Glue together mold segments	chemical : skin exposed to toxic chemical Glues can be hazardous	Minor Likely	Low	Gloves, buy non-hazardous glues.	Minor Remote	Negligible	On-going [Daily] Sean
2-3-1	Manufacturer/Research assistant Cut hypotubing	mechanical : cutting / severing Any cutting tool is capable of also cutting you	Moderate Unlikely	Low	Practice good workholding	Moderate Unlikely	Low	On-going [Daily] Ben
2-3-2	Manufacturer/Research assistant Cut hypotubing	mechanical : pinch point Pinch fingers in vice	Moderate Unlikely	Low		Moderate Unlikely	Low	On-going [Daily] Hailey
2-3-3	Manufacturer/Research assistant Cut hypotubing	slips / trips / falls : debris Burrs and sparks ejected by the cutting tool	Minor Likely	Low	Wear eyeprotection and long sleeves/pants/closed toed shoes	Minor Unlikely	Negligible	On-going [Daily] Biren
2-3-4	Manufacturer/Research assistant Cut hypotubing	noise / vibration : noise / sound levels > 80 dBA	Minor Very Likely	Medium	Ear plugs.	Minor Unlikely	Negligible	On-going [Daily] Sean
2-4-1	Manufacturer/Research assistant Insert Hypotubing	mechanical : cutting / severing Metal tubing and burrs can puncture skin	Serious Unlikely	Medium	Deburr and sand ends of tubing	Serious Remote	Low	On-going [Daily] Ben
2-4-2	Manufacturer/Research assistant Insert Hypotubing	mechanical : pinch point Hypotubing is inserted in small holes	Moderate Remote	Negligible	Keep fingers clear of holes	Moderate Remote	Negligible	On-going [Daily] Hailey

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-5-1	Manufacturer/Research assistant Mix silicone	ergonomics / human factors : repetition Mixing	Minor Likely	Low		Minor Likely	Low	On-going [Daily] Biren
2-5-2	Manufacturer/Research assistant Mix silicone	chemical : reaction to / with irritant chemicals Silicone can be an irritant	Moderate Likely	Medium	Use food-grade silicone mix and wear gloves	Minor Remote	Negligible	On-going [Daily] Sean
2-5-3	Manufacturer/Research assistant Mix silicone	chemical : skin exposed to toxic chemical Silicone can be an irritant	Moderate Likely	Medium	Use food-grade silicone mix and wear gloves	Minor Remote	Negligible	On-going [Daily] Ben
2-6-1	Manufacturer/Research assistant Pour silicone	chemical : reaction to / with irritant chemicals Silicone can be an irritant	Moderate Likely	Medium	Use food-grade silicone mix and wear gloves	Minor Remote	Negligible	On-going [Daily] Hailey
2-6-2	Manufacturer/Research assistant Pour silicone	chemical : skin exposed to toxic chemical Silicone can be an irritant	Moderate Likely	Medium	Use food-grade silicone mix and wear gloves	Minor Remote	Negligible	On-going [Daily] Biren
2-7-1	Manufacturer/Research assistant Apply vacuum	mechanical : crushing Vacuum can pull and pinch surfaces together	Moderate Unlikely	Low	Use adequate vacuum chamber	Moderate Remote	Negligible	On-going [Daily] Sean
2-7-2	Manufacturer/Research assistant Apply vacuum	mechanical : drawing-in / trapping / entanglement Vacuum might pull in skin	Moderate Unlikely	Low	Use adequate vacuum chamber	Moderate Remote	Negligible	On-going [Daily] Ben
2-7-3	Manufacturer/Research assistant Apply vacuum	mechanical : break up during operation Vacuum pump engines must be maintained and well oiled	Catastrophic Likely	High	Remember to oil before use and don't leave running overnight	Catastrophic Unlikely	Medium	On-going [Daily] Sean
2-7-4	Manufacturer/Research assistant Apply vacuum	noise / vibration : noise / sound levels > 80 dBA Vacuum pumps are noisy	Minor Very Likely	Medium	Wear ear plugs and minimize time spent around vacuum pump	Minor Unlikely	Negligible	On-going [Daily] Hailey

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-7-5	Manufacturer/Research assistant Apply vacuum	fluid / pressure : vacuum vacuum	Moderate Unlikely	Low	Use adequate vacuum chamber	Moderate Remote	Negligible	On-going [Daily] Biren
2-8-1	Manufacturer/Research assistant Seal belt	chemical : skin exposed to toxic chemical Silicone filler can be toxic	Minor Unlikely	Negligible	Buy safe silicone filller	Minor Remote	Negligible	On-going [Daily] Sean
2-9-1	Manufacturer/Research assistant Punch ports	mechanical : cutting / severing Bipsy punch is made to cut human skin	Serious Unlikely	Medium	Train user, wear cutting glove	Serious Unlikely	Medium	On-going [Daily] Ben
3-1-1	Pilot Maintain aircraft and flight conditions	slips / trips / falls : falling material / object If the adhesive fails, the belt might fall from the aircraft and damage some flight equipment	Catastrophic Remote	Low	Test transfer adhesive, ensure proper clamping proceudre is followed, use speed tape to further restrain belt.	Catastrophic Remote	Low	On-going [Daily] Hailey
4-1-1	passer by / non-user Walk under airplane	slips / trips / falls : debris If the adhesive fails, the belt might fall from the aircraft and hit someone	Moderate Remote	Negligible	Test transfer adhesive, ensure proper clamping proceudre is followed, use speed tape to further restrain belt.	Moderate Remote	Negligible	On-going [Daily] Biren
4-1-2	passer by / non-user Walk under airplane	slips / trips / falls : falling material / object If the adhesive fails, the belt might fall from the aircraft and hit someone	Moderate Remote	Negligible	Test transfer adhesive, ensure proper clamping proceudre is followed, use speed tape to further restrain belt.	Moderate Remote	Negligible	On-going [Daily] Sean

Appendix O: Operator's Manual

Parts List

- PLA Mold
- Cores – 0.036" Stainless Steel Hypodermic Tubing – From McMaster-Carr
- Petroleum jelly
- 2-part silicone – "SORTA-Clear 40" – From Manufacturer
- Mixing Cup and Mixing implements – Any disposable cup will work.
- Vacuum chamber
- Vacuum pump
- Blue/Yellow Epoxy Putty – "Green Stuff"
- Isopropyl alcohol
- 3M Transfer Adhesive 45120 or 45128 – From manufacturer
- 3M Glass Foil Tape – "Speed Tape" – From manufacturer
- Handheld Vacuum Pump
- Dental Pick
- Biopsy Punch
- 0.042" Vacuum Tubing

PPE List

Nitrile Gloves

Manufacturing Steps

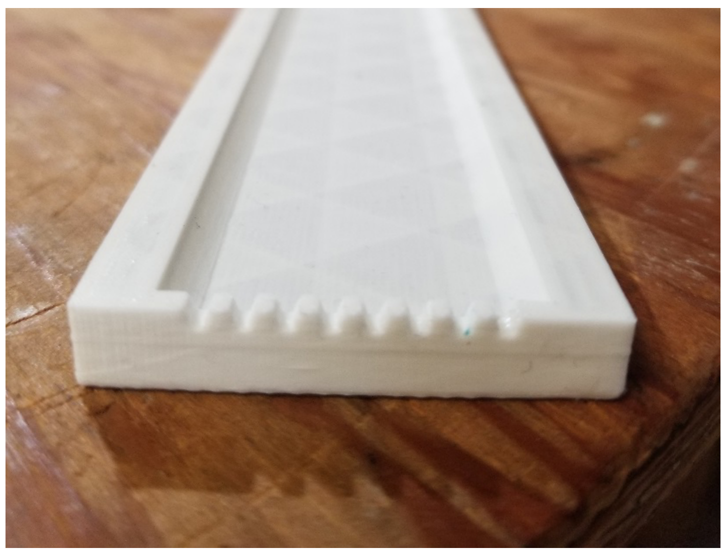
NOTE: For a more detailed reference of best practices and pitfalls for properly manufacturing the silicone belt, see the Manufacturing plan section of the design report.

This plan assumes that a mold of your desired length and shape has already been 3D printed and prepared, and that you have cores of the desired length.

1. Prepare the cores for insertion into the mold.
    a. USE CAUTION when handling cores. Cores can have sharp ends after cutting them, which may pierce the skin. Cores are also delicate, meaning they can be bend easily. Hold the cores by the middle whenever possible to reduce the possibility of bends happening.
    b. Ensure that all cores are straight. A straight core should roll easily on a flat surface (a MICRO-FLAT would be ideal for this check).
    c. Ensure all cores are long enough for the mold being used. Cores should stick out at least 0.5" from one end of the mold. This is just to ensure there is enough material to grab onto when the cores are removed.

d. Coat the cores in a thin layer of petroleum jelly by liberally placing petroleum jelly on the core itself, and then wiping away the excess using a paper towel. The resulting coating should be thin, but still present.

2. Insert the cores into the mold.
    a. The mold's design allows for the cores to be dropped in through the V-shaped cuts in either end. Place all cores being used into the mold.



    b. Ensure that no cores are touching each other or the bottom of the mold. An easy way to ensure the cores are not touching the bottom of the mold is to use a flashlight. If light can be shined in such a way that the shadow of the core is not touching the core itself, the core is not touching the bottom of the mold.
    c. Use the blue modeling clay to fill in the remainder of the V-shaped gap in the mold, thus locking in the cores and sealing off the mold.
3. Mix and degas the two-part silicone.
    a. The SORTA-Clear silicone manufacturer specifies a 10:1 ratio of part A to part B. We used 5g of part A per linear inch of belt for our configuration. This is a food-grade silicone (intended for making food molds) and is safe to handle, but gloves are still recommended to reduce contact with chemicals.
        i. For the 10.5" configuration, 50g of Part A and 5g of Part B is the appropriate quantity of silicone.

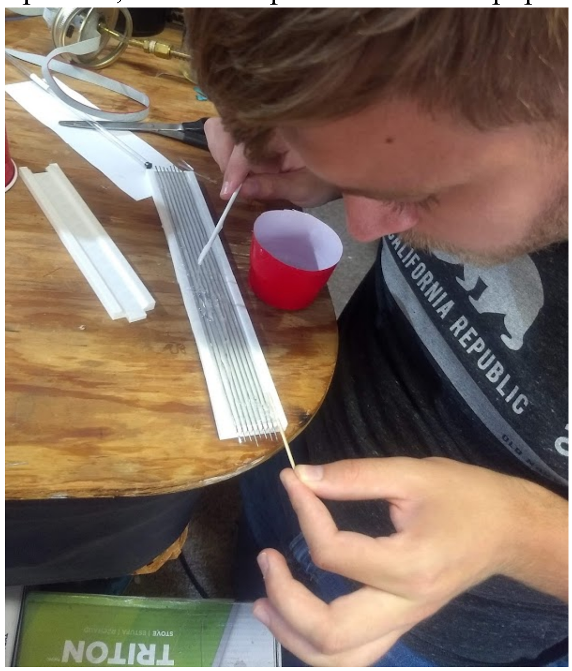
b. Mix slowly and thoroughly (about 2-3 mins). Use a cup sized such that there is 1”-2” of depth to the mixture. Avoid “whipping” and “folding” the mixture to minimize adding air bubbles. Be sure to scrape down the sides of the cup to ensure the two parts are thoroughly combined.
c. Place the cup in a vacuum chamber with at least 1.5” of clearance between the surface of the mixture and the top of the chamber.

d. Pull at least a 29 inHg vacuum using the vacuum pump. USE CAUTION: Ensure that the pump has sufficient oil and does not run dry.
e. Wait for an airy foam layer to form and collapse above the surface of the mixture as a check that the vacuum chamber is functioning. After 5-7 mins of continuous vacuum, the vacuum process is complete, and the mixture can be removed from the chamber. The result should be a transparent with little to no air bubbles.

4. Pour the silicone over the top of the mold. Ensure the silicone flows under all cores and through the length of the belt.

a. Because of the v’s in the mold, it could be useful to put the cores in at this stage. Pouring half of the silicone before inserting the cores can be an effective way to ensure that there is ample material below the cores. After this, pour the rest of the silicone as normal.

5. Use a heat gun to bring any remaining bubbles to the surface. These bubbles should pop on their own. USE CAUTION: Heat guns are hot. Use quick back-and-forth strokes at least 2 feet away from the surface of the belt and do not overheat any areas. Overheating rapidly cures the silicone making the heated surface hard and prevents any further modification.
6. If there are still bubbles present, use a toothpick or needle to pop them.



7. Allow the silicone to cure for ~18 hours.

Assembly

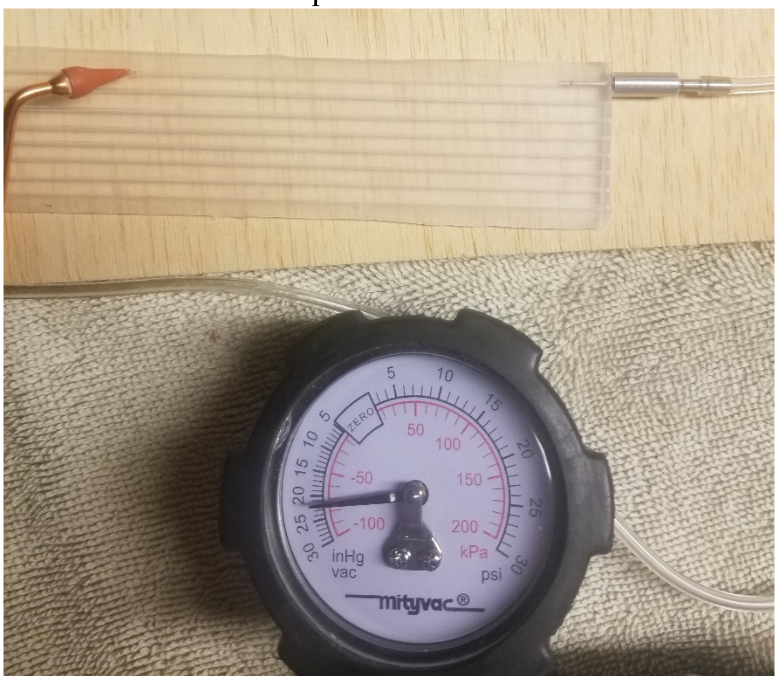
1. Once cured, remove the belt from the mold by lifting up on the left end of the belt. A straight edge can be used to pry the belt out if necessary and required little to no force. NOTE: Do NOT pull up on the cores. Lifting on the cores could rip the vias or bend the cores.
2. Use a biopsy punch to create pressure ports on the top surface of the belt at desired locations (the surface that cured against the mold).
3. GENTLY pull the cores from the belt with needle nose pliers. Do not bend the cores. The cores should pull with relative ease, and if not, require more petroleum jelly coating for future iterations.
4. Seal the front end of the belt by applying a small amount of silicone to the belt end. This can be done with a popsicle stick, and the belt should be left to cure horizontally. (I.e., laying on the face that would sit on the wing)
5. Individual segments can be joined together with 0.042” tubing to make longer belts.

Belt Testing

These tests must be performed on each belt. They determine if the belt has been manufactured properly and ensure that the pressure data will be accurate.

Leak Test

1. Insert the pump nozzle into one end of a specific via to be checked.
2. Insert and hold dental pick into the other end of the same via to seal off the end.



3. Pump the hand pump to 25psi of vacuum on the pressure via. Observe the potential decrease in pressure on the gauge on the pump.
4. For the specific via to pass this test, the via must hold pressure for 30 seconds. Ensure that no leaks are coming around the nozzle or dental pick.
    a. This test ensures that there is no way for the belt to obtain a pressure reading from any other location other than the pressure port that will be cut later.
5. Perform the Flow Test for this via.
6. Repeat this test for all pressure vias.

Flow Test

1. After a leak test, take the dental pick out without removing the pump nozzle.
2. Pump the hand pump 3-4 times and check to see if any vacuum is being held by the pressure via.
    a. A pass on this test will have no pressure held by the unsealed pressure via. This ensures there are no blockages in the pressure via.

3. Repeat this process for each via after each leak test.

Installation

1. Clean surface thoroughly, using isopropyl alcohol and a microfiber rag to remove any contaminants on the surface.
2. Apply transfer adhesive tape to all parts of the surface to which the belt will attach.
3. Pull the backing and place the belt onto the transfer adhesive. Press down on top of the belt for at least 30 seconds at all points on the belt. This ensures a secure bond between the silicone and the transfer adhesive.
4. Apply speed tape to all edges of the belt, securing all the edges to the surface. Use a spreader to completely smooth all tape. This ensures wind cannot get under the belt and rip it off the surface it is attached.

Maintenance/Repair

No maintenance should be required for this belt. If anything occurs that yields the belt unusable, it is best to construct another belt using the previously described methods.

STL files are available for mold reprints.

Cores can be re-cut to size after reordering from McMaster-Carr if they become too damaged.

Resources

Transfer adhesive manuals available at https://www.3m.com/3M/en_US/p/d/b40065897/

SORTA Clear data sheet available at https://www.smooth-on.com/tb/files/SORTA_CLEAR_SERIES_TB.pdf

SORTA Clear MSDS available at https://www.smooth-on.com/msds/files/BD_DS_Eco_Equ_EZB_EZS_Psy_MS_OOMOO_Reb_ST_SS_Soma_Sol_Sorta.pdf

Appendix P: Test Procedures

Test Procedure #1

Test Name: Leak Test

Purpose: Determine if individual vias can hold pressure

Scope: This test proves if the pressure belt can transfer accurate pressure measurements to the BLDS (without any interference from leaks)

Equipment: Specialized hand pump, rubber dental picks, silicone pressure belt

Hazards: None

PPE Requirements: None

Facility: Sean's garage

Procedure: (List number steps of how to run the test, can include sketches and/or pictures):

1. Place dental pick into the end of an individual via to create a seal.
2. Place hand pump nozzle into the other end of the via.
3. Pressurize each via to 20 psi by pumping air into the vias.
4. Verify that each via can maintain the set pressure for at least 10 seconds using the pressure gage on the hand pump.

Results: Pass Criteria, Fail Criteria, Number of samples to test
Pass criteria: Able to maintain set pressure for 10 seconds.
Fail criteria: Unable to maintain set pressure for 10 seconds.
Number of samples: Test each via of the belt

Test Date(s): PER BELT
Test Results:

Via Criteria		Via Number							
		1	2	3	4	5	6	7	8
Visual Inspection	Does probe fit in via appropriately?								
	Are there any visual occlusions between vias?								
	Is via free of obstruction at either end?								

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Pressure Check	**Does via hold 20 psi of pressure after holding for 15 seconds?**								
Comments									

Performed By: Sean

Test Procedure #2

Test Name: Flow Test

Purpose: Determine if individual vias will allow air to flow through, to test if the via is obstructed

Scope: This will allow us to determine if pressure can be transmitted through each of the vias – this must be performed on each belt. This test, in conjunction with the leak test, ensures that each via will only take pressure from the port itself, and that none of the vias are connected to each other.

Equipment: Specialized vacuum hand pump, silicone belt

Hazards: None

PPE Requirements: None

Facility: Sean's garage

Procedure:

1. Visually inspect via for things blocking flow through it
2. Insert hand pump nozzle into pressure via.
3. Pump hand pump multiple times.
4. Observe pump gauge – it should quickly drop off if there are no obstructions in the belt preventing flow.
5. Perform steps for each via in the belt.

Results:

- Pass Criteria: Pass on all checks in list below
- Fail Criteria: Fail in any check below.
- Number of Samples: Test all pressure belts.

Pass Criteria Checklist

	Does the belt have anything visibly blocking the via? Pass if nothing appears to be blocking	Does the nozzle fit well into the pressure via? Pass if the nozzle fits in securely	Does the belt hold pressure when pumped without anything blocking the via's other end? Pass if no pressure is held.
Pass/Fail			

Test Date(s): PER BELT
Test Results:
Performed By:

Test Procedure #3

F61 Pressure Belt
Test Name: Void Check/Via Bridging Visual Inspection

Purpose: Ensure that the vias in the belt have not bridge and are not at risk of bridging due to any stretching or wear that occurs during installation. This test is essentially a sanity check for our leak and flow tests. This test will be performed on every belt we manufacture and should be done on all future belts our sponsor manufactures as well.

Location: The test will take place in Sean's garage where we are currently designing all our prototypes after each iteration.

Scope: Tests entire length of the cast belt section.

Equipment:

- Magnifying glass
- Long, blunt needle or wire
- Marking device
- Powerful Backlight source

Hazards: At failure, the readings off the belt might be inaccurate.

PPE Requirements: None

Facility: Sean's garage

Procedure: (List number steps of how to run the test, can include sketches and/or pictures):

1. Remove cores from belt casting.
2. Place belt on backlight or otherwise orient the light so it shines through the belt clearly.
3. Run magnifying glass down one via, locating and marking any potentially problematic bubbles that surround it.
4. Repeat process for all vias.
5. If necessary, insert needle or wire into via and check all potentially problematic bubbles to ensure that it cannot penetrate through to any other vias.
6. Remove needle from belt. Turn off backlight.

Additionally, an "auditory" inspection can be performed by hooking one via up to an air compressor and plugging the port on the other end of the via and listening for leaks.

As we iterate through different outgassing methods, we will keep a tally of how many problematic bubbles we detect to help determine which method is most effective. That is the only data we will be collecting.

Results:
Pass Criteria: No problematic bubbles are determined to have bridged across vias, nor are they likely to do so given (as determined by the user, Dr. Russel Westphal)

Fail Criteria: There is potential bridging between two vias or a thin wall between a bubble and via that is likely to puncture during the flight test or installation.
Number of samples to test: All.

Safety Concerns:
The needle/wire should be blunt, but still care should be taken in handling it.
Be aware of focal effects of the magnifying glass to avoid damaging any equipment with heat.

Test Date(s): 4/25 (Perpetual)
Test Results:

Performed By: Sean Casteel

Test Procedure #4

F61 Pressure Belt

Test Name: Adhesive Shear Force Test

Purpose: Determine the shear force required to remove belt with adhesive from wing model

Scope: Test how strong the adhesive is

Equipment: Spring scale, adhesive, silicone belt, airfoil surface/wing model, vise to hold wing model

Hazards: At failure, the belt could spring suddenly off the wing surface.

PPE Requirements: Eye protection

Facility: Sean's garage

Procedure: (List number steps of how to run the test, can include sketches and/or pictures):

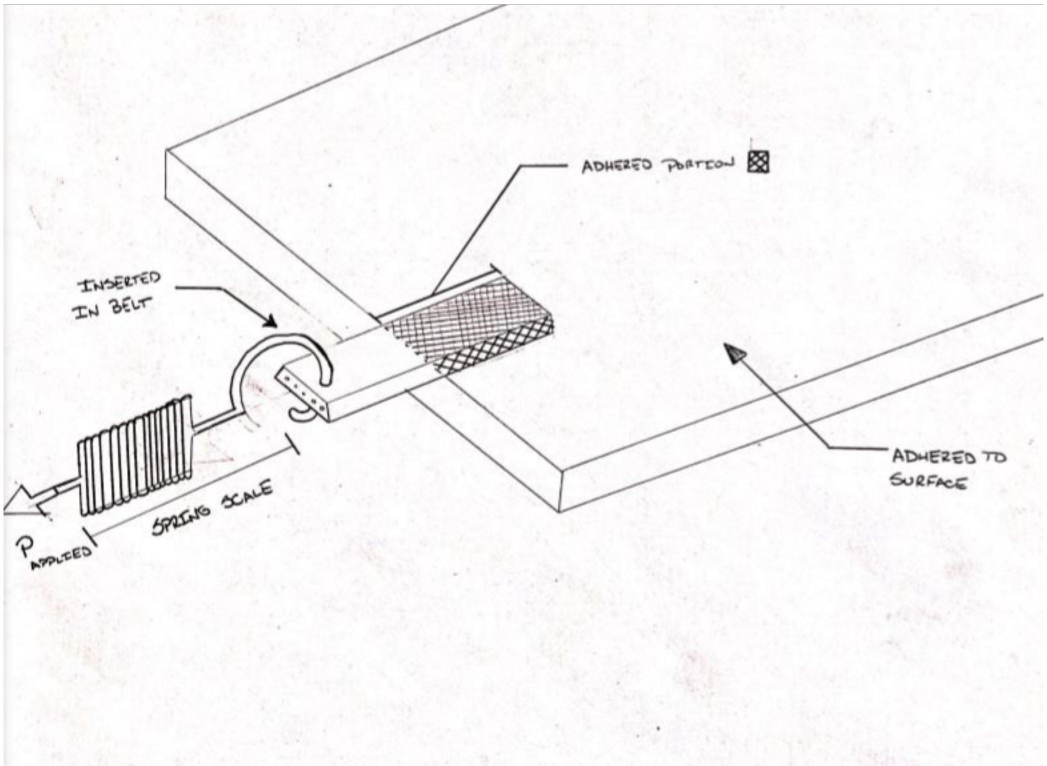
1. Apply adhesive to belt (rectangular area) and measure surface area of adhesive.

	Length(in) + Uncertainty	Width (in) + Uncertainty	Area (in^2)	Cure Time (min)
Test 1:				
Test 2:				
Test 3:				

2. Place adhesive onto surface
3. Attach end of spring scale to belt.
    a. Attach end of spring scale to belt by puncturing hook through silicone test belt.
4. Apply force to end of spring scale.
5. Measure force at yield - either

	Force at yield (lbf) + uncertainty	Failure Mode (glue vs. silicone rupture)	Area (in^2)	Shear stress at yield (psi)
Test 1:				
Test 2:				
Test 3:				

6. Repeat process 3 times.



Results:
Pass Criteria: Yield occurs after 2psi.
Fail Criteria: Yield occurs before 2psi.
Number of samples to test: 3

Test Date(s): 4/30
Test Results:

Performed By: Sean